High speed running and repeated sprinting in male academy football players

This thesis is submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy.

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DECLERATION OF ORIGINALITY

This work is original and has not been previously submitted in support of a degree qualification or other course.

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ABSTRACT

High speed running and repeated sprinting are component parts of training and match play among academy football players. Despite players having to self-pace running speed and the intervening recovery periods during match play, the way these qualities are trained and tested are often externally regulated with specific work-to-rest ratios and prescribed intensities. The aims of this thesis were to investigate high speed running separated by externally regulated and self-selected recovery periods under conditions that replicate training and testing practices analogous with football. Under controlled conditions replicating training practices common amongst academy players, Chapter 4 showed that high speed running and repeated sprinting separated by externally regulated recovery periods resulted in running speeds that differed by a smaller magnitude than those used in their prescription. These data question the fidelity of this approach and the ability of players to replicate prescribed running speeds in the field. Data from Chapter 4 also demonstrated that neuromuscular function was *likely* reduced 14 hours after high speed running (-5.6%; ES –0.44 ± 0.32; P = 0.01) and combination running (-6.8%; ES -0.53 ± 0.47; P = 0.07) . During 10 x 30 m repeated sprints there was a *most likely* higher percentage decrement (65%; 0.36 ± 0.21; P = 0.12) and *most likely* increased physiological load evidenced by between sprint heart rate recovery (-58.9%; ES -1.10 ± 0.72; P = 0.05) when sprints were interspersed by self-selected compared to externally regulated recovery periods (Chapter 5). Performance decrements were, however, attenuated in more mature players (Chapter 6). When considering biological maturity, pre-PHV players displayed a lower percentage decrement (2.1 ± 1.1%) than post-PHV (3.2 ± 2.1%) players across all sprints when recovery periods were externally regulated (37%; ES 0.41 ± 0.51; P = 0.03). When self-selected recovery periods were used, percentage decrement was lower in the post-PHV group. In Chapter 7, ratings of perceived exertion were used to guide

running speed and recovery distribution during a high speed running test performed to volitional exhaustion. Peak running speed in the self-paced (21.8 ± 1.4 km·h^{-1}) was *likely* (4.1%: ES 0.63 ± 0.43; $P = 0.03$) higher than in the externally regulated YYIRT1 (20.9 ± 1.1 km·h^{-1}); however, average running speed in the self-paced (13.5 ± 1.2 km·h^{-1}) was *likely* (6.5%; ES 0.67 ± 0.51; $P = 0.05$) slower (12.7 ± 1.6 km·h^{-1}). There was a moderate difference in total between shuttle recovery periods (13.3%; ES 0.58 ± 0.81; $P = 0.16$) in the self-paced (552 ± 132 s) compared to externally regulated versions (634 ± 125 s) of the YYIRT1. When exposed to running drills separated by self-selected and externally regulated recovery periods, academy footballers allocate insufficient recovery to preserve running performance and are unable to differentiate between sprinting and high speed running when prescribed according to specific speeds (Chapter 4) and subjective ratings of exertion (Chapter 7). Prescribing self-paced high intensity running interspersed with self-selected recovery periods results in higher physiological loads when compared to externally regulated recovery intermissions and therefore should be considered during training programmes that target adaptations in aerobic capacity. Despite this, where coaches are using high speed running programmes to improve speed and/or speed endurance, externally regulated recoveries are likely to result in the preservation of performance across the repetition range and, as such, are more beneficial to the intended adaptation.

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Preparing this thesis, from the planning (I'm joking, I didn't plan any of it) through data collection and into preparing the final manuscript has taught me how little I know about my chosen discipline, something that has, I am pleased to say, been a welcome lesson. I feel fortunate to work in an industry where inquiry is at the heart of good practice and where the challenge of improving performance in both sport and exercise is as relevant now as it ever has been. This is even more pertinent given the excellent work undertaken by esteemed colleagues, peers, academics, practitioners and those who pioneered the field in its early years.

Although it is my name on the front, a cast of thousands have contributed to what is detailed on the pages that follow. Many will not be aware of their contribution; I include in this the athletes I have been fortunate to work with over the years and who have provided a constant source of perspective and challenge along with the teachers, lecturers and conference speakers who have inspired me. There are, however, some people who I think deserve a special mention.

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And finally, to my family, Ann Marie, Harry Glynn and Ava Grace Gibson. My words for you cannot be transcribed, they are for only you to hear, whispered in the space between the dying of the light and the rising of the sun, in the minutes when I lie awake and realise how fortunate I am.

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PUBLICATIONS FROM THIS THESIS

Gibson, N., Henning, G., and Twist, C. (2018). Movement characteristics, physiological and perceptual responses of elite standard youth football players to different high intensity running drills. *Science and Medicine in Football,* 2(4), 281-287.

Gibson, N., Brownstein, C., Ball, D., and Twist, C. (2018). Physiological, perceptual and performance responses associated with self-selected versus standardized recovery periods during a repeated sprint protocol in elite youth football players: A preliminary study. *Paediatric Exercise Science,* 29(2), 186-193.

Brownstein, C., Ball, D., Micklewright, D., and **Gibson, N.** (2018). The effect of maturation on performance during repeated sprints with self-selected versus standardized recovery intervals in youth footballers. *Pediatric Exercise Science,* 30(4), 500-505.

ADDITIONAL CONTRIBUTIONS TO THE FIELD

In addition to the published articles identified above, the following publications and outputs have arisen from the completion of this thesis:

McEwan G, Arthur R, Phillips S, **Gibson N,** and Easton C**.** (2018) Interval running with self-selected recovery: physiology, performance and perception. *European Journal of Sports Science,* 18;8, 1058-1067.

Gibson, N. (2018) High intensity interval training: why adjusting recovery periods could boost your fitness. *The Conversation*.

BASES workshop on the use of self-selected recovery periods when prescribing high intensity interval training entitled 'Don't wait for the beep' (28th March 2019; Oriam: Scotland's sports performance centre, Edinburgh, Scotland).

Gibson, N and McCunn, R. (2019) Don't wait for the beep. *Sport Science and Performance Reports,* 47;1, 1-3.

Gibson, N, (2019) Presentation at the annual UKSCA conference entitled 'Don't wait for the beep; non-traditional approaches to prescribing work to rest ratios'. (09th June 2019; MK Don's stadium, Milton Keynes, England)

CHAPTER 1: GENERAL INTRODUCTION

1.1 Academy football

Professional and amateur football (association football) clubs globally have developed training and competition programmes to facilitate the development of players toward becoming adult professionals, often termed academies. Despite the proliferation of such academies, our knowledge of how best to develop and prepare these young players is incomplete with many approaches, at least to the physical conditioning of players, having been designed, in the first instance, for adults (McMillan, Helgerud, Macdonald, & Hoff, 2005). It is commonplace for academies to control the development of young players between the ages of ten and nineteen years of age, a period that encompasses a number of physical (Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004) and cognitive (Piaget, 1954) stages of development. The accelerated period of somatic growth which in males occurs around 14 years of age is characterised by changes in a number of physiological and cognitive systems which likely affect at least to some degree how individuals respond to different training approaches (Malina et al., 2004). As such further investigation is warranted regarding responses of academy footballers to commonly used training and testing practises.

1.2 High speed running and repeated sprinting

High speed running, including sprinting and repeated sprinting occur in training, match play and the physical assessment of academy football players (Castagna, D'Ottavio, & Abt, 2003; Deprez, Vaeyens, Coutts, Lenoir, & Philippaerts, 2012; Faude, Schnittker, Schulte-Zurhausen, Muller, & Meyer, 2013; Harley et al., 2010). During match play youth footballers cover around 12% of total distance in high speed running activities (Rebelo, Brito, Seabra, Oliveira, &

Krustrup, 2014) which is similar to that reported for adults, whilst the prevalence of repeated sprinting characterised as two or more sprints with less than 30s between each is low (Carling, Le Gall, & Dupont, 2012; Schimpchen, Skorski, Nopp, & Meyer, 2016). From a training perspective, players must develop the necessary physical characteristics to successfully compete in the adult game (Helsen, Hodges, Van Winckel, & Starkes, 2000), where the ability to perform high intensity running is a key component in successful performance during match play (Bradley et al., 2009; Di Mascio & Bradley, 2013). As well as the ability to perform high speed running, players, young and old must develop the ability to know 'when' to display this quality so that their effort results in the intended outcome whilst not jeopardising performance later in the match or training session. The perceptual element of high speed running has received less attention than the physiological underpinning. Despite a lack of research in this area, the skill is an important component of successful performance; players must develop the ability to interpret spatial and temporal cues to employ their physical attributes in the most effective manner. Spatial awareness refers to an understanding of the distance that is required to be covered in order to affect the desired outcome. For example, whilst it has been established that a 0.02s improvement in 20m sprint time represents a real change when engaged in a contest for the ball, players must decide how close they need to be to the ball or opponent in relation to when the sprint is initiated. Temporal awareness relates to the associated recovery time required between each running effort so that performance can be sustained for the duration of the match, training session or, more acutely, during the next high intensity effort. Players must learn to assimilate this information in order to know when to perform high speed running to yield the most effective outcome, this is especially pertinent given the prevalence of straight line sprints that precede goals (Faude, Koch, & Meyer, 2012)

1.3 High speed running and repeated sprinting as a training modality

High speed running and repeated sprinting is an effective training modality amongst youth and adult football players (Dupont, Akakpo, & Berthoin, 2004; Faude et al., 2013; Ingebrigtsen, Shalfawi, Tonnessen, Krustrup, & Holtermann, 2013; Tonnessen, Shalfawi, Haugen, & Enoksen, 2011). Their prescription has included intervals completed over various distances (Ingebrigtsen et al., 2013; Tonnessen et al., 2011), durations (Macpherson & Weston, 2015) and at different speed thresholds (Faude et al., 2013; Haugen, Tonnessen, Leirstein, Hem, & Seiler, 2014). The intensity of intermittent exercise, however, is a function of the duration and speed of intervals combined with the recovery afforded between successive efforts or repetitions. To date, research in academy football players performing high speed running has focused on manipulating the intensity of exercise rather than recovery duration. Further investigation is warranted regarding how different approaches to scheduling recovery might affect performance during high intensity interval training (Castagna, Manzi, Impellizzeri, Weston, & Barbero Alvarez, 2010; Dupont & Berthoin, 2004; McMillan, Helgerud, Macdonald, et al., 2005).

1.4 Recovery from high speed running and repeated sprinting

It has been reported that children possess a well-developed capacity for aerobic metabolism but, compared to adults, might be disadvantaged in activities relying more on anaerobic metabolism (Armstrong, Barker, & McManus, 2015; Armstrong & Welsman, 2001; McNarry & Jones, 2014; Ratel, Williams, Oliver, & Armstrong, 2006). For example, aerobic fitness, assessed under laboratory conditions and reported as VO_2 peak has been reported to increase from 1.78 ± 0.24 l·min^{-1} to 3.55 ± 0.55 l·min^{-1} in boys aged 11 and 17 years respectively (Armstrong & Welsman, 2001). For the older participants cited above, VO_2 peak is reflective of a non-trained population; values of 4.87 ± 0.45 $l \cdot min^{-1}$ were reported for similarly aged academy footballers (McMillan, Helgerud, Macdonald, et al., 2005). Values for healthy adult males have been reported as 4.5-4.91 $l \cdot min^{-1}$ whilst for professional footballers this increases to 5.81 [range: 4.21-6.18] $l \cdot min^{-1}$ (Helgerud, Rodas, Kemi, & Hoff, 2011). The improvement in aerobic fitness is paralleled by less favourable changes in power output during maximal sprinting. During ten, 10 s sprints on a non-motorised treadmill separated by 15 s boys (11.7 ± 0.5 years) were able to maintain performance to a greater degree than men (22.1 ± 2.9 years) for peak power output (17.7 cf. 43.3% decrement), mean power output (28.9 cf. 47.0% decrement) and running velocity (18.8 cf. 29.4% decrement), respectively (Ratel, Williams, et al., 2006). Furthermore, when recovery was increased to 10 s between sprints there were no significant changes in any performance measures within the boys but significant decrements in both peak (7.7%) and mean (7.8%) power amongst the men (Ratel, Williams, et al., 2006). Despite inferior performance during the 'all out' tasks (e.g. sprinting), boys recover more rapidly between successive bouts of high intensity exercise than men (Ratel, Lazaar, Williams, Bedu, & Duche, 2003). This is attributed to physiological factors including enhanced oxidative capacity (Kaczor, Ziolkowski, Popinigis, & Tarnopolsky, 2005), faster re-synthesis of phosphocreatine stores between successive bouts of fatiguing exercise (Ratel, Tonson, Le Fur, Cozzone, & Bendahan, 2008; Willcocks, Fulford, Armstrong, Barker, & Williams, 2014), differential motor unit recruitment and usage (Dotan et al., 2012; Metaxas et al., 2014), an attenuated slow component associated with fatigue resistance (Poole & Jones, 2012; Rossiter, 2011) and more efficient removal of metabolic by-products (Falk & Dotan, 2006) when compared to adults. As such, adopting different work to rest ratios for young football players may be advantageous in maximising the effectiveness of training programmes that comprise high intensity intermittent exercise. In adults, reducing the between interval recovery duration had a negative effect on performance during high intensity treadmill running (Balsom, Seger, Sjodin, & Ekblom, 1992) with similar responses reported for repeated sprinting in young football players (Padulo et al., 2015). In both instances, however, recovery duration and the resultant work to rest ratio was prescribed *a priori* which does not permit players to select what they perceived to be an optimal rest period.

1.5 Self-selected recovery

Given the greater propensity for aerobic energy provision and faster recovery between bouts of high intensity exercise in adolescents (Armstrong et al., 2015), pre-determined recovery periods designed for adults may be too long for younger players with less advanced biological maturation. The range of recovery durations that could be prescribed to intersperse interval lengths reported in the literature, although not infinite, is large enough to make identifying the optimal work to rest ratio for each individual problematic. An alternative approach to using specific and prescribed recovery periods is to allow the individual performing the intervals to self-select recovery duration after being provided with a clear aim for the session. Prompts, for example, may include '*ensure you maintain your maximal speed in each repetition*' when the aim of training is to maximise speed or speed endurance, whilst a prompt of '*allow the minimum amount of recovery to maintain a maximal effort in each repetition'* may be efficacious when the aim of training is to provide a conditioning stimulus through elevated heart rate levels. Whilst the use of self-selected recovery periods have been investigated in adults (Glaister et al., 2010; McEwan, Arthur, Phillips, Gibson, & Easton, 2018; Phillips, Thompson, & Oliver, 2014) it has not reported in younger populations and may provide a useful means of prescribing training for large groups, the likes of which are common in football academies given that players can conduct the training without the need for a coach to indicate when to 'stop' and 'go'. Furthermore, utilising self-selected recovery durations may assist in the development of temporal cues as players need to interpret the time required to recover between successive efforts so that their performance matches the aim of the session.

1.6 Spatial and temporal cues

The use of self-selected recovery periods during high intensity interval training and assessment is complicated by previous research that has suggested young people lack the ability to interpret temporal and spatial cues (Chinnasamy, St Clair Gibson, & Micklewright, 2013; Micklewright et al., 2012) during continuous exercise. In the context of football specific exercise, spatial and temporal cues represent the ability of players to tactically position themselves on the pitch, be that during training or match play. During football specific exercise, players are required to time and disguise their movements to gain an advantage over opponents. They are also required to apportion their effort so that they are able to complete the requirements of their role and position for the duration of the match or for the duration of their involvement, whichever is longer (Waldron & Highton, 2014). The interaction of spatial and temporal cues allow players to do this. For example, a player may occupy a space when defending that prevents their opponent from making their preferred pass whilst allowing them to reposition themselves effectively should the direction of play change. Understanding the spatial requirements of their position and the proximity to both opponents (spatial) combined with knowing when to initiate a run that will reposition them after play moves on (temporal) is a vital skill for footballers. In summary, temporal cues relate to an understanding of how long it takes to cover required distances whilst spatial cues inform their positioning on the pitch so that the required distance can be covered in the time afforded.

The ability to identify these cues and respond accordingly are skills believed to develop concurrently with biological maturation. Despite this, few studies have investigated the ability of academy footballers to interpret spatial and temporal cues during discrete actions that occur during football specific exercise such as intermittent high speed running. This is particularly pertinent given that in applied settings players are often asked to, during high speed running, cover a specific distance in a specified period of time, a task requiring the interaction of temporal (how fast do I need to run) and spatial (what is the distance I need to cover) cues so that they arrive at a specified point in the specified time (Dupont et al., 2004). Current practice during high speed running drills utilise recovery periods that are pre-determined and, as such, removes the necessity for players to interpret their own readiness to recommence exercise in line with the aim of the session (Ingebrigtsen et al., 2013; Tonnessen et al., 2011). The requirement to self-select recovery periods interspersing high speed running repetitions requires players to interpret temporal cues so that they allowed sufficient recovery between efforts to maintain performance whilst achieving the intended physiological load.

1.2 Aims and scope of the thesis

The aim of this thesis was to investigate how movement characteristics, physiological and perceptual responses were affected during high speed running drills when adolescent football players were allowed to self-select recovery periods separating efforts and self-pace the runs they interspersed compared to when these variables were externally controlled or prescribed *a priori*.

This aim will be addressed through four empirical studies:

Study 1 examined the movement characteristics, physiological and perceptual responses associated with different high intensity running drills, comprising high speed running, repeated sprinting and a combination of the two, in academy football players. The data showed that despite differences in the speeds used to prescribe the high speed runs and repeated sprints, actual movement characteristics were similar. Furthermore, when performing the runs in combination rather than in series, peak running speed during high speed runs was augmented whilst speed over the initial 4s during repeated sprints was compromised. The data raised questions around the fidelity of prescribing high speed running in the field and the ability of academy football players to differentiate between the requirements of different intensities associated with this type of training.

Study 2 investigated the performance, physiological and perceptual responses associated with externally regulated versus self-selected recovery periods in academy footballers during repeated sprinting. The data showed that when self-selected between sprint recoveries were employed, sprint time and percentage decrement increased compared to externally regulated recovery, this was likely the result if participants allocated less total recovery. Although there were decrements in performance the physiological load associated with repeated sprints separated by self-selected recovery was higher supporting the use of prescribing repeated sprints in this way as a conditioning tool.

Study 3 explored the effect of biological maturation on performance, physiological and perceptual responses during repeated sprints interspersed with self-selected and externally regulated recovery periods. Participants were allocated to a pre or post peak height velocity group and performed a repeated sprint task comprising 10 x 30 m efforts under two experimental conditions; self-selected and externally regulated recovery. The data showed that while the pre peak height velocity group performed better in the externally regulated recovery condition, evidenced by a lower percentage decrement compared to their more mature peers, this was reversed when self-selected recovery periods were employed. These data suggest that younger people appear less able to interpret temporal cues and that this skill may improve with advancing biological maturation. Performance in the self-selected recovery condition was, however, still compromised in the more mature group compared to when externally regulated recovery was used. Similarly to study two, physiological load was higher in the self-selected recovery trial.

Study 4 examined the movement characteristics and physiological responses associated with an externally regulated and self-paced version of the YoYo Intermittent Recovery Test Level 1 in academy footballers. Each trial was performed until volitional exhaustion with running speed and recovery distribution in the self-regulated recovery trial allocated according to the rating of perceived exertion recorded in the externally regulated version of the test. Although total distance and end heart rate were similar, movement characteristics of peak and average speed were different between trials at exercise performed at the same rating of perceived exertion. These differences were less pronounced at higher running speeds corresponding to ratings of perceived exertion of 19-20.

CHAPTER 2 – REVIEW OF LITERATURE

2.1 Academy football – the annual plan

The typical season for academy footballers, those aged between 7 and 19 years old, in Scotland, the country in which data for this thesis was collected, is markedly different from their professional counterparts. The season runs from August through to June with a month-long break over the Christmas period and intermissions in the training calendar that mimic school holidays. Training occurs on a Tuesday, Wednesday and Friday evening commencing at 17:30. Matches are generally played on a Saturday and Sunday however where there are fixture cancellations due to inclement weather, matches can and are played in the evenings replacing training. Match durations range from 60 to 90 minutes comprising 3 x 20 min periods or 2 x 45-minute periods depending on the age of the players competing.

Up until the age of 16 players are signed to part time contracts and train three nights per week with sessions lasting ~90 min in addition to two strength sessions performed prior to training and lasting 45 min. The contracts preclude the players from training or playing with any other team. Whilst players can continue to be part time up until the age of 19 years of age, most players transfer to full time training at the age of 16 years where their training shifts to mornings and early afternoons with circa 4-5 sessions per week. The number of weekly sessions can often be lower for full time academy players compared to their part time counterparts due to the number of squads they can be included in. For example, a 17 year old full time academy player may play for an academy team at the weekend and then be included in a reserve squad on a Tuesday night. With the requirement for recovery sessions this match schedule limits the amount of training that can be performed.”

2.2 Movement characteristics and physiological responses football specific exercise

2.2.1 Challenges in assessing the movement demands of academy football players

Determining the movement characteristics of academy football players during match play is complicated by the non-uniform playing time at different age groups (Goto, Morris, & Nevill, 2015; Harley et al., 2010; Mendez-Villanueva, Buchheit, Simpson, & Bourdon, 2013), lack of consensus regarding the delineation of speed thresholds and the effect that maturation has on speed during adolescence (McCunn, Weston, Hill, Johnston, & Gibson, 2017; Philippaerts et al., 2006). At present, there is no consensus regarding how high speed running should be categorised in academy football players (Drust, 2018). Despite this, governing bodies have suggested that professional football academies use micro-technology to quantify external load. Therefore, the standardisation of speed thresholds is important in ensuring that accurate assessments of external load can be made longitudinally and especially in instances where a player's development is managed by different clubs and when on international duty.

Running speeds between 13.0 $km{\cdot}h^{-1}$ to 18.0 $km{\cdot}h^{-1}$ have been categorised as high speed (Castagna et al., 2010; Goncalves, Figueira, Macas, & Sampaio, 2014), a range that, at the lower end, is representative of the lactate threshold (McMillan, Helgerud, Grant, et al., 2005) and at the upper end, the maximal aerobic speed reported for academy football players (Buchheit et al., 2015). This relatively broad range (5 $km{\cdot}h^{-1}$) likely corresponds to different internal loads, characterised by heart rate and ratings of perceived exertion depending on both fitness status and stage of maturation, making meaningful inferences regarding overall load problematic (McLaren et al., 2018). To address this issue, individualised approaches to quantifying high intensity running have used maximal aerobic speed, i.e. the speed corresponding to the final stage of a modified version of the Montreal Track test (Mendez-Villanueva et al., 2013), velocity associated with the with the final level achieved in the YoYo

Intermittent Recovery test (level 1) (Buchheit et al., 2015) and percentages of maximal sprint speed (Harley et al., 2010). Given the impact that maturity has on maximal aerobic speed (Buchheit, Simpson, & Mendez-Villanueva, 2013) and sprint speed (McCunn et al., 2017), this approach to classifying high intensity running may also provide issues in the longitudinal tracking of this quality. Future research may wish to focus on methodological and practical issues of individualising thresholds (Drust, 2018), specifically, which method, if any, exhibits the greatest degree of stability during the period players are within an academy setting so as to allow accurate longitudinal tracking and analysis. Given that a range of different approaches to individualising movement characteristics in female football players did not enhance the dose-response determination over a short, 21-day training camp (Scott & Lovell, 2018), practitioners must assess the time/benefit ratio in such analysis. The classification of repeated sprint sequences in academy football players is more clearly established, defined as two or more sprints greater than 1 s duration with 60 s or less separating them (Buchheit & Mendez-Villanueva, 2013; Buchheit, Mendez-villanueva, Simpson, & Bourdon, 2010b).

2.2.2 Movement characteristics during football specific exercise

Football specific exercise can be broadly characterised as training and match play. In youth football, which has received less attention than the adult game, pitch dimensions are variable with reduced dimensions for younger age groups in both training and match play, often with fewer players per team for younger age groups and alternate strategies for dealing with substitutes (Harley et al., 2010; Saward, Morris, Nevill, Nevill, & Sunderland, 2016).

During match play, movement characteristics, defined as total, high speed, low speed and sprinting distance, increased non-linearly as players became chronologically older, however factors other than playing position, age or success in terms of retention by their club appeared to be responsible for this increase (Saward et al., 2016). The categorisation of running thresholds has become more detailed as technology has advanced, specifically the development of global positioning technology (GPS) capable of sampling at a higher frequency and worn by players between the shoulder blades replacing camera-based systems. In youth football this is evidenced by the categorisation of high speed running in a study conducted in 2003 as being actions above 13·1 $km.h^{-1}$ with maximal running denoted by those above 18·0 $km.h^{-1}$ (Castagna et al., 2003). The study in question utilised camera technology to track players and calculate the velocity of movement, an approach that has been shown to exhibit low absolute error and consistent levels of error when compared to GPS at low to moderate running speeds (Palucci Vieira, Carling, Barbieri, Aquino, & Santiago, 2019). Studies published in 2010 (Buchheit, Mendez-villanueva, et al., 2010b; Harley et al., 2010) and 2015 (Arruda et al., 2015; Saward et al., 2016) using GPS to track running performance have been able to report high speed actions in greater detail.

Total distance covered during match play reported relative to playing time for youth footballers ranges from 98.0 $m{\cdot}min^{-1}$ to 114 $m{\cdot}min^{-1}$ for players aged between nine and eighteen years of age with high speed running ranging from 25 $m.min^{-1}$ to 50 $m.min^{-1}$ albeit with different thresholds and calculation methods adopted (Arruda et al., 2015; Buchheit & Mendez-Villanueva, 2014b; Harley et al., 2010; Saward et al., 2016). Whilst examining running performance based on absolute (Buchheit, Mendez-Villanueva, Simpson, & Bourdon, 2010a; Castagna et al., 2003) speed thresholds allows the examination of changes over time, a number of studies have extolled the benefits of individualised speed thresholds (Harley et al., 2010; Saward et al., 2016) with associated commentaries provided (Drust, 2018). Despite advances in how we classify and categorise running actions there is still a lack of understanding surrounding how young players develop the ability to apportion physical efforts during match play, i.e. not just ‘can’ I run but do I know ‘when’ to run?. Indeed, more successful youth players appear to cover more low intensity running than their less successful counterparts which may allow them to position themselves more appropriately, negating the need for as many high speed actions to recover poor positioning (Saward et al., 2016)

Longitudinal studies focusing on movement characteristics associated with youth footballers are not as prevalent in the literature as those conduced in adult participants. Furthermore, the same methodological considerations as were reported for match play exist in terms of how movement demands are calculated (absolute versus relative thresholds). Studies that have been reported for youth footballers have tended to focus on full time youth footballers rather than part time. The total weekly volume of running reported for full time youth players aged 17 years is 29342 m over a period of 6 weeks which included 26 training sessions, 13 rest days and 6 competitive matches (Fitzpatrick, Hicks, & Hayes, 2018) equating to an average of 4887 m per week. This is considerably lower than values reported for a planned micro cycle of training among similarly aged players competing in the same competition who covered 18967 m on average in training alone (Malone et al., 2015). High speed running, although calculated using different thresholds, equated to an average of 435 m and 233 m respectively. These studies may be indicative of the effect that different coaching styles and approaches to training have on movement characteristics.

Unpublished data from part time players competing in the same competition as those from whom data is presented in this thesis covered between 10 and 15 km total distance as a result of 2-3 scheduled sessions over the course of a week, with high speed running accounting for around 5% of total distance (unpublished data collected in part time players within a Scottish Premier League academy). More research is required to understand the running characteristics of individual sessions within micro and macro cycles performed by youth footballers, especially where this data is used to better understand how training is impacting selected indices of fitness (Faude et al., 2013; Ingebrigtsen et al., 2013).

2.2.3 Physiological responses to football specific exercise

The most commonly used marker to assess the physiological or internal load associated with football specific exercise is heart rate. It has been reported, albeit in adult players that the mean and peak heart rate values achieved during a match are 85 and 98%, respectively, which corresponds to an average oxygen uptake of 70% VO_{2max} (Bangsbo, Mohr, & Krustrup, 2006). These values are slightly higher than those recorded during training in youth academy players which ranged between 68 and 76% of maximum. Given the propensity of younger people for aerobic metabolism, combined with the relatively slower speeds achieved when engaged in high speed running, these data support the high reliance on aerobic metabolism that soccer specific exercise induces. Indeed, positive changes in fitness represented as increases in VO_{2max} and running economy have been reported in youth football players when supplementary conditioning training was scheduled according to heart rate (McMillan, Helgerud, Macdonald, et al., 2005). As well as informing the intensity of prescribed training, heart rate can be used to quantify how well young players are recovering from training and/or match play. Heart rate recovery has been used following a variety of exercise protocols, generally sub-maximal in nature, to quantify the fatigue response and have been shown to be a useful tool in the monitoring of football players (Bradley, Di Mascio, Bangsbo, & Krustrup, 2012; Buchheit, Simpson, Al Haddad, Bourdon, & Mendez-Villanueva, 2012).

Despite the use of heart rate as a monitoring tool in football players it may not accurately reflect the overall intensity of training characterised by high speed intermittent running or sprinting over short distances (Buchheit et al., 2012). Where training is characterised by short, intermittent activities, monitoring tools that are more sensitive to anaerobic activity may be more suitable. For example, Padulo et al. (2015) used blood lactate as a marker to interpret the intensity of repeated sprinting which has been used as a training modality for football players (Tonnessen et al., 2011). Blood lactate concentration has also been used in adult players to explain, in conjunction with heart rate responses, the intensity of match play and simulated match play (Mohr, Krustrup, & Bangsbo, 2005). The usefulness of blood borne markers in youth players as a tool to assess the intensity of short term, high intensity exercise should be viewed in conjunction with the fact that younger people have a greater propensity for aerobic metabolism and, as such, a lower reliance on the glycolytic pathways that stimulate lactate production (Tonson et al., 2010). Whilst the role of glycolytic activity in children is unclear, partly due to methodological differences in how various substrates are measured (Kappenstein et al., 2013; Tonson et al., 2010; Zanconato, Buchthal, Barstow, & Cooper, 1993), data suggest that an increase in anaerobic energy metabolism can be achieved through the re-phosphorylation of ATP via anaerobic pathways (Hug, Bendahan, Le Fur, Cozzone, & Grelot, 2005). The faster appearance and subsequent clearance of blood lactate in children compared to adults has been attributed to increased monocarboxylate transporters expression, larger membrane transport capacity and enhanced blood flow through shorter intramuscular perfusion distances (Tonson et al., 2010). Indeed, an improved matching of perfusion to metabolic rate has been associated with the response to training in children (McNarry & Jones, 2014).

The greater propensity for aerobic metabolism and recovery from high intensity exercise in children may also be the result of structural and enzymatic adaptations such as a greater expression of phosphofructokinase (PFK), a rate limiting step in the Krebs cycle (Paraschos et al., 2007). A greater number of aerobic enzymes, lower muscle volume and a greater density of capillarisation may all facilitate the acute recovery process (Dipla et al., 2009; Hamilton, Nevill, Brooks, & Williams, 1991). Furthermore, the enhanced ability to produce energy via aerobic pathways may act to limit acidosis and speed the re-synthesis of phosphocreatine (PCr). Indeed the half-life of PCr recovery has been shown to be much less in children aged 6-12 compared to adults (Taylor, Kemp, Thompson, & Radda, 1997).

As well as internal and external markers of load associated with match play and training, subjective measures have been employed in the literature, principally, ratings of perceived exertion (RPE). In under 17 youth football players no change in RPE 48 hours after a competitive match was detected when compared to pre match, yet increases at 24 hours when compared to pre and 48 hours post were reported (Djaoui, Diaz-Cidoncha Garcia, Hautier, & Dellal, 2016). When multiple games were played within the space of 48 hours, youth players did not report any change in their post-match RPE (Moreira et al., 2016). In contrast, when 4 matches in 4 days were simulated to assess the efficacy of cold water immersion, RPE scores following a 5 min submaximal run increased across the investigation period (Garvican et al., 2014). Collectively these data suggest that RPE values may be sensitive to subjective changes in exertion as a result of match play.

When RPE was used to represent the exertion associated with respiratory and muscular function after training and match play over a nine-week period it was shown to discriminate between elite and non-elite players (Gil-Rey, Lezaun, & Los Arcos, 2015) with the elite group recording much higher values. How much of this difference was the result of intensity is difficult to assess as the training duration of the two groups were not matched. Indeed, in a nine-week training study within professional youth football players, individual training impulse derived from heart rate (iTRIMP), but not sessional RPE, showed the greatest correlation to changes in fitness assessed using the lactate threshold (Akubat, Patel, Barrett, &

Abt, 2012). The use of differential RPE scales may provide a useful alternative when assessing responses to match play, however their use has not as yet been reported in youth players (Weston, Siegler, Bahnert, McBrien, & Lovell, 2015). Despite the potential benefit of using these scales and their ability to differentiate the source of fatigue their use has been associated with moderate to high within-player variability (Weston et al., 2015).

The reporting of RPE appears to be unaffected by the timing of its collection and the order of activities undertaken within the preceding training session (Fanchini, Ghielmetti, Coutts, Schena, & Impellizzeri, 2015). Whilst this is useful for practitioners when facing the logistical challenges of RPE collection it does raise the question of whether these perceptual markers are sufficiently sensitive to changes in training intensity such that modifications in the prescribed stimulus can be changed as a result.

Table 1: Thresholds and categorisation of high intensity running and repeated sprinting during match play in academy male football players.

Author	Age group	Demographic	Method of analysis	High intensity running thresholds	High intensity running totals (m)	Sprint thresholds	Sprinting totals (m)	Repeated sprinting criteria
Da Silva et al., 2007	Under 15s Under 17s Under 20s	Brazilian youth	Video analysis				303.1 ± 82.6 m 477.6 ± 235.2 m 599.6 ± 233.2 m	N/A
Goncalves et al., 2018	18.1 ± 0.7 y	Portuguese youth	5 Hz GPS	>13.0 – 17.9 $km \cdot h^{-1}$	Not reported	>18.0 $km \cdot h^{-1}$	Not reported	N/A
Mendez-Villanueva et al., 2013	Not reported	Highly trained youth	1 Hz GPS	% of maximal aerobic speed and anaerobic speed reserve	Not reported	N/A	Not reported	N/A
Buchheit et al. 2013	14.5 ± 1.3 y	Highly trained youth	1 Hz GPS	>19 $km \cdot h^{-1}$	Not reported	>61% individual sprint speed	Not reported	N/A
Buchheit et al., 2015	16.0 ± 0.4 y	Highly trained	10 Hz GPS	Not reported	Not reported	>19 $km \cdot h^{-1}$ or 61% of individualised peak velocity	Not reported	2 or more ≥ 1 s with no more than 60 s recovery
Mendez-Villanueva et al., 2011	16.7 ± 1.7 y	Young football players	1 Hz GPS			Peak game speed		

Buchheit et al., 2010	14.5 ± 1.7 y	Young football players	1 Hz GPS			>19 $km \cdot h^{-1}$ or 61% of individualised peak velocity		2 or more ≥ 1 s with no more than 60 s recovery
Castagna et al., 2009	14.1 ± 0.2 y	Young football players	1 Hz GPS	13.0 - 18.0 $km \cdot h^{-1}$	468 ± 89 m	>18 $km \cdot h^{-1}$	114 ± 73 m	N/A
Castagna et al., 2003	11.8 ± 0.6 y	Male outfield football players	Video analysis	13.0 – 18.0 $km \cdot h^{-1}$	468 ±89 m	>18 $km \cdot h^{-1}$	114 ± 73 m	N/A
Harley et al., 2010	12 – 16 y	Elite youth football players	5 Hz GPS	4.18 – 5.04 $m \cdot s^{-1}$	1713 ± 371 at U12 to 2481 ± 1044 m at U16	5.32 – 6.41 $m \cdot s^{-1}$	174 ± 64 m at U12 to 302 ± 184 m.	N/A

2.2.4 High speed running and repeated sprint sequences

Absolute distance covered in high intensity running is greater in older (16 years) compared to younger (12 years) players during match play (Harley et al., 2010). However, when expressed relative to minutes played, younger players have been shown to cover the same (Harley et al., 2010), more (Mendez-Villanueva et al., 2013) and less distance in high speed running than their older peers (Da Silva, Kirkendall, & Neto, 2007). Such disparity may be the result of different thresholds used in the classification of high speed running combined with technical and tactical aspects during match play which have been shown to influence movement characteristics in adult players (Saward et al., 2016). However, the disparity highlights the challenge of tracking players across multiple seasons and using the resultant data to guide their longitudinal development. Table 1 details the various methods and thresholds used to characterise high speed running.

The number of repeated sprint sequences during match play reduces between 12 and 18 years of age (Buchheit, Mendez-villanueva, et al., 2010b; Saward et al., 2016), with fewer sequences still in adult match play (Carling et al., 2012). Furthermore, between sprint recovery intermissions increase in duration as players become older; the highest frequency of repeated sprints separated by the shortest intermission (15 s) were observed in 12 year old players (Buchheit, Mendez-villanueva, et al., 2010b). It would appear, therefore, that the number, recovery intermission length and frequency of repeated sprint sequences is inversely correlated with increases in high speed running and sprint speed (Buchheit & Mendez-Villanueva, 2014a) as well as age and maturation (Carling et al., 2012). This might be explained by the adoption of more effective positioning strategies and game awareness as the experience of players increases, negating the requirement to sprint as frequently. Indeed, adolescent players have been shown to cover more low intensity activity during match play than adults (Saward et al.,

2016) which might, albeit speculatively, be the result of less well developed positional awareness. Age, playing position and match exposure (Da Silva et al., 2007; Mendez-Villanueva et al., 2013; Saward et al., 2016) all play a role in determining how much high speed running and repeated sprinting youth football players undertake during match play.

During a single match, ratings of perceived exertion (RPE) were lower in the first half than second, despite higher levels of both internal (Aslan et al., 2012) and external load (Castagna et al., 2003) in the former. During a period of intensified competition that elicited increases in stress hormone concentration in adolescent players, RPE remained unchanged (Moreira et al., 2016).

2.2.6 Monitoring responses to training and match play

Adolescent players are subjected to single (Harley et al., 2010) and multiple matches (Arruda et al., 2015) interspersed by regular and organised training sessions (Malone et al., 2015). As such researchers and practitioners are interested in assessing how training and match play impacts on various physiological and physical parameters both during and after competition (Malone et al., 2015). A range of protocols exist by which to monitor players following training and match play including autonomic function, biochemical markers, self-reported wellness and measures of lower body muscle function (Fitzpatrick, Akenhead, Russell, Hicks, & Hayes, 2019). An important consideration when choosing an assessment protocol by which to investigate the effect that training and match play has is the reliability of the measure. That is, how confident those administering the test can be that a change is ‘real’ and as a result of the preceding exercise rather than normal biological variation.

Two popular measures in team sport athletes for monitoring the response to training and match play are subjective measures of wellness and lower body muscular function. Despite subjective measures of wellness being used in adult team sport players (McLean, Coutts, Kelly, McGuigan, & Cormack, 2010) their use in youth football players have been questioned regarding their ability to detect a change in performance over and above the noise associated with the test (Fitzpatrick et al., 2019). When assessing lower body muscle function, commonly used tests include the countermovement jump and derivatives thereof (Gathercole, Sporer, Stellingwerff, & Sleivert, 2015). Measures reported to show acceptable reliability include peak power and flight time when assessed during a countermovement jump in adults (Gathercole et al., 2015) and peak power when assessed in student rugby league players (Johnston et al., 2013). Conjecture exists around the use of countermovement jump height as a monitoring tool in youth footballers (Fitzpatrick et al., 2019; Malone et al., 2015).

2.3 Mechanisms of fatigue following high intensity exercise

2.3.1 Muscle characteristics and neuromuscular fatigue

Regular squad training in academy players did not affect countermovement jump performance despite marked changes in the external load experienced by players during the microcycle (Malone et al., 2015). Conversely, countermovement jump performance was impaired following match play and training in adult team sport athletes (Cormack, Mooney, Morgan, & McGuigan, 2013; Cormack, Newton, McGuigan, & Cormie, 2008; McLean et al., 2010; Mooney, Cormack, O'Brien B, Morgan, & McGuigan, 2013). Changes in neuromuscular function following intense exercise may also differ between players at different stages of maturation. When peak force was adjusted according to thigh volume during 50 maximal knee extensions at 3.14 $rad{\cdot}s^{-1}$ decrements in force were less in 14 year olds (36%) than 18-15 year olds (48%) (Kanehisa, Okuyama, Ikegawa, & Fukunaga, 1995). To what extent training status may affect this decline in fatigue resistant qualities is unclear. Training programmes targeting improvements in neuromuscular function, for example, have shown increases in force expression and a reduction in peripheral fatigue in ten year old boys (Skurvydas, Brazaitis, Streckis, & Rudas, 2010). Conversely, type II muscle fibres associated with high force production and increased fatigability (Colliander, Dudley, & Tesch, 1988), increased with age but were independent of training history (Metaxas et al., 2014; Van Praagh & Dore, 2002). Further research is required to understand how best to quantify neuromuscular fatigue in well trained academy football players following high intensity exercise.

2.3.2 Changes in blood and muscle metabolites

The direct assessment of metabolites associated with fatigue presents logistical and ethical concerns when dealing with young players who are part of professional academies. As such, indirect methods have been more prominent in the literature; blood lactate has been used to quantify internal load in academy football players with higher values measured during the first compared to second half of match play (Aslan et al., 2012). Blood lactate however exhibits a poor relationship with muscle lactate during match play in adults (Krustrup et al., 2006). Furthermore, neither muscle lactate nor pH were correlated with the decline in sprint performance as match play progressed in adults (Krustrup et al., 2006). These data suggest that whilst blood lactate may be indicative of peripheral fatigue, it is not a primary cause of detrimental changes in performance during match play. Despite this, during a repeated sprint assessment higher blood lactate levels were associated with detrimental changes in performance during a repeated sprint assessment characterised by reduced between sprint recovery intermissions (Padulo et al., 2015).

Beta-hydroxyacyl-Co-A dehydrogenase (HAD) and PFK are rate limiting enzymes within the Krebs cycle and important in energy provision via aerobic pathways (Paraschos et al., 2007) . Strong correlations were reported between distance covered, distance deficit from the first to second half, total high speed running distance and maximal HAD activity, whilst greater sprint distances was correlated with higher levels of PFK in adult players (Mohr, Thomassen, Girard, Racinais, & Nybo, 2016). Furthermore, peak periods of high intensity running were correlated with Na^{+}-K^{+} ATPase sub-unit protein levels (Mohr et al., 2016) which play a crucial role in buffering capacity within the active musculature. These data suggest that players with a greater capacity to produce energy through aerobic pathways and limit the detrimental effects of anaerobic exercise and the associated metabolic by-products, one of which being blood lactate, may be more able to produce high running speeds during the most intense periods of match play. Indeed, high intensity training in the form of high speed running and sprinting enhances buffering capacity and Na^{+}-K^{+} ATPase sub-unit protein concentrations. Whilst the collection of biopsies in academy footballers is challenging, the YoYo Intermittent Recovery test levels one and two were demonstrated to be useful surrogate markers of HAD and PFK, respectively (Mohr et al., 2016), with better performance in the assessment associated with high concentrations of the aforementioned enzymes.

2.4 Field based assessments of high speed running and repeated sprint ability

2.4.1 High speed running

Assessments of high speed running ability in academy footballers have included a modified version of the University of Montreal Track Test (Dupont et al., 2010), the YoYo intermittent recovery and endurance assessments (Bangsbo, Iaia, & Krustrup, 2008; Saward et al., 2016), 30-15 intermittent fitness test (IFT) (Buchheit & Rabbani, 2014) and 20 m multi stage fitness test (Meckel, Machnai, & Eliakim, 2009). Whilst the relationship between performance in different assessments of high speed running has been investigated (Buchheit & Rabbani, 2014), the appropriateness of each will likely reflect its intended aim, be that for selection purposes (Waldron & Murphy, 2013), individualising training intensities (Buchheit, 2008b), studying the effect of maturation (Mendez-Villanueva et al., 2010) or investigating the relationship with match running performance (Buchheit, Mendez-Villanueva, et al., 2010a).

The 20 m multi stage fitness test has been used to quantify maximal aerobic power in academy football players (Bellistri et al., 2017; Meckel et al., 2009; Svensson & Drust, 2005). Furthermore, the derived estimation of VO_{2max} can be used to calculate maximal aerobic speed. Despite this, protocols such as the 30-15 IFT and YoYo assessments, characterised by intermittent running, are cited as being more representative of the demands of match play (Buchheit & Rabbani, 2014). Indeed, maximal speed and those corresponding to the ventilatory threshold were higher in the 30-15 IFT compared to 20 m multi stage fitness test whilst cardiorespiratory responses were moderately to well correlated (Buchheit, Al Haddad, et al., 2009). Albeit in adolescent team sport players rather than football *per se*, the maximal running speed attained in the 30-15 IFT is highly correlated to physiological variables elicited during continuous running in the 20 m multi stage fitness test and University of Montreal Track Test, as well as markers of aerobic power, explosive lower limb power and cardiorespiratory recovery (Buchheit & Rabbani, 2014). When compared to continuous shuttle running the 30-15 IFT appears to account for several physiological variables simultaneously.

The YoYo assessment, at least in practical settings, is regularly used amongst male academy footballers. Levels one and two of the YoYo intermittent recovery assessment exhibit acceptable reliability across a range of sports, standards of competition and ages whilst taxing aerobic and anaerobic energy systems (Bangsbo et al., 2008; Krustrup et al., 2003). Furthermore, significant correlations were observed between maximum speed during the YoYo intermittent recovery test and maximal aerobic velocity during continuous running in male academy football players (Dupont et al., 2010). This relationship, however, was not constant; when the final speed in both assessments was greater than 16.3 $km \cdot h^{-1}$ the value recorded in the continuous assessment tended to be higher. When final speeds were below 16.3 $km \cdot h^{-1}$ the converse was true and the maximal speed during intermittent running tended to be higher (Dupont et al., 2010). These data are important if the resultant speeds are being used to prescribe high speed interval training (Dupont et al., 2004) and may prompt practitioners to choose different protocols for players within the same squad, or for different age groups. Practitioners must balance the desire to track players longitudinally using the same protocol for all age groups against the most appropriate protocol for specific stages of development and fitness.

The Yo-Yo intermittent recovery protocol is reliable amongst academy football players and able to differentiate between playing standards and age groups with older and higher standard players covering greater distances (Bradley et al., 2011). Practitioners may also employ the intermittent endurance version of the YoYo assessment protocol which starts at slower speeds than the intermittent recovery test and employs shorter, 5 compared to 10 s, between shuttle recovery periods (Castagna, Impellizzeri, Chamari, Carlomagno, & Rampinini, 2006). Despite slower speeds during the intermittent endurance test, shorter recovery periods ensure that the aerobic system is taxed maximally, evidenced through percentage heart rate values in academy players close to 100% (Bradley et al., 2011). For this reason the assessment may be better suited to players at the lower end of the academy age range, especially those yet to experience peak height velocity, given the greater propensity for aerobic metabolism reported amongst this population (Malina et al., 2004; McNarry & Jones, 2014). Equally, the endurance versions (levels 1 and 2) of the YoYo assessment may not be suitable for those whose final score is likely below 16.3 $km \cdot h^{-1}$ and when the resultant data are being used to inform training prescription (Dupont et al., 2010).

As well as reliability, the validity of assessments that measure high speed running ability is an important consideration (Rampinini et al., 2007). Performance in the YoYo intermittent recovery level 1 has been positively correlated with distance covered in high speed running during match play, defined as speeds between 13.0-18.0 $km \cdot h^{-1}$ (Castagna, Impellizzeri, Cecchini, Rampinini, & Alvarez, 2009). These results have not been corroborated in more recent studies in which high speed running was more closely related to playing position (Buchheit et al., 2013), maturation and body dimensions (Buchheit & Mendez-Villanueva, 2014b). High speed running was defined in the aforementioned studies as >19.0 $km \cdot h^{-1}$ and 16.1-19.0 $km \cdot h^{-1}$, respectively, highlighting the difficulty in assessing performance in field based assessments with match demands. Both versions of the YoYo intermittent running test detect differences between playing position and playing standard along with changes associated with chronological age (Bradley et al., 2011; Krustrup et al., 2003). These data would, in tandem with appropriate methods to detect 'real' change (Veugelers, Naughton, Duncan, Burgess, & Graham, 2016), support their use in the longitudinal tracking of academy football players. No studies to date have investigated the relationship between performance in the 30-15 IFT and match activity; however, this is not what the test was designed for. The validity of the protocol has been established for the identification of velocity at VO_{2max} and as a tool to establish and individualise high intensity running speeds (Buchheit, 2008a; Buchheit, Al Haddad, et al., 2009; Buchheit & Rabbani, 2014).

2.4.2 Repeated sprint ability

Repeated sprint assessments have used a range of repetitions, sprint distances and recovery lengths to assess physical qualities in academy football players. Protocols used in football are shown in Table 2. Protocols include straight line sprints (Aziz, Mukherjee, Chia, & Teh, 2007; Chaouachi et al., 2010; Ingebrigtsen et al., 2014; Ingebrigtsen et al., 2013) and change of direction (da Silva, Guglielmo, & Bishop, 2010; Ferrari Bravo et al., 2008; Gibson, Currie, Johnston, & Hill, 2013) over 6-7 repetitions of 20 – 43.2 m (Aziz et al., 2007; Barbero-Álvarez, Pedro, & Nakamura, 2013; Chaouachi et al., 2010; Gibson et al., 2013; Mujika, Spencer, Santisteban, Goiriena, & Bishop, 2009; Padulo et al., 2015) and recovery intervals ranging from 20 – 30 s (Buchheit, Mendez-Villanueva, Delhomel, Brughelli, & Ahmaidi, 2010; Ferrari Bravo et al., 2008; Huijgen, Elferink-Gemser, Lemmink, & Visscher, 2014). Protocols have utilised variable recovery durations, ranging from 15 to 25 s (Padulo et al., 2015), and scheduling recovery time as a function of sprint performance (Barbero-Álvarez et al., 2013; Buchheit, Mendez-Villanueva, Delhomel, et al., 2010). Although such repetition ranges are in excess of those reported during match play (Buchheit, Mendez-villanueva, et al., 2010b) other protocols have employed 10 (Tonnessen et al., 2011) and 15 (Haugen et al., 2015) efforts over distances ranging from 20 – 40 m. Whilst 10-15 when compared to 6-7 repetitions may provide a greater challenge to the ATP-PC and glycolytic energy systems, their ecological validity in terms of movement characteristics observed during match play should be questioned. One assessment that more closely resembles the number of repeated efforts observed in match play comprised 3 x 30 m sprints with three, 180^{o} changes of direction and interspersed by 20 s of recovery (Huijgen et al., 2014); however, from an applied perspective this does not appear to be commonly used.

An inherent challenge when interpreting data from repeated sprint assessments is the lack of a ‘gold standard’ measure for fatigue (Glaister, Howatson, Pattison, & McInnes, 2008). This is unlike measures of high intensity running which can be validated against laboratory derived values for VO_{2max} and running speeds associated with its attainment. This may explain the breadth of protocols for the assessment of repeated sprint ability. Regarding outcome measures and how performance is assessed it appears that percentage decrement is the most reliable, calculated using total sprint time and 'ideal' sprint time (ideal time is a function of the fastest sprint multiplied by the number of repetitions) (Glaister et al., 2008). These metrics, unlike mean and best sprint time, ensure participants attempt to replicate, in each repetition, their best possible sprint performance.

Field-based assessments of repeated sprint ability comprising six or more sprints exhibit a positive relationship with match demands including high intensity running above 13.0 $km \cdot h^{-1}$ and peak speed (Barbero-Álvarez et al., 2013), standard of competition (e Silva et al., 2010) and playing position (Aziz, Mukherjee, Chia, & Teh, 2008). Whilst these data would support the use of repeated sprint assessments as proxy measures of performance during match play, the prevalence of repeated sprint sequences in competition reduces as players become chronologically older (Buchheit, Mendez-villanueva, et al., 2010b). Given the improvement in technology that allows the assessment of movement characteristics during match play there is less requirement for proxy measures. Indeed, recent research would suggest that repeated sprinting is an independent rather than dependant quality; something that should be trained but not necessarily tested (Taylor, Macpherson, Spears, & Weston, 2016). Not all practitioners working with academy footballers will have access to micro-technology that allows in-depth analysis of movement characteristics during match play and training. For these groups the use of measures such as repeated sprinting to inform which players may be, physiologically at least, better equipped to cope with the demands of match play are warranted.

The ability to perform repeated sprints interspersed with limited and incomplete recovery requires well developed maximal sprinting speed (Mendez-Villanueva et al., 2011), lower body power (Spencer, Bishop, Dawson, & Goodman, 2005) and maximal aerobic capacity (Spencer, Pyne, Santisteban, & Mujika, 2011). Indeed, repeated sprint performance, in assessment protocols at least, improves in academy footballers during peak height velocity (Malina, 1994; Mujika et al., 2009) a period during which there is an increase in muscle fibre size (Van Praagh & Dore, 2002), recruitment of type IIa motor units (Dotan et al., 2012) and maximal aerobic capacity (Philippaerts et al., 2006). Maximal running speed, however, can both increase (Beunen & Malina, 1988; Mendez-Villanueva et al., 2010) and decrease (McCunn et al., 2017; Philippaerts et al., 2006) before peak height velocity, with the greatest decrements reported for the fastest players (Mendez-Villanueva et al., 2010). These data highlight the importance of establishing the physiological mechanisms and systems which underpin changes in repeated sprint performance before using the resultant data to direct future training or to inform decision regarding selection and de-selection.

In a sport that is characterised by high speed running and sprinting, it is important to consider how these two qualities interact with each other, especially as training programmes will likely address them in tandem (Faude et al., 2013). The relationship between repeated sprint ability and high speed running, however, may depend on the protocol employed. For example, stronger relationships are reported between the YoYo intermittent recovery test level 1 and repeated sprint ability for distances ≤ 20 m (Chaouachi et al., 2010), whereas performance in the YoYo intermittent recovery test level 2 may be more representative of performance in assessments that use distances in excess of 20 m (Ingebrigtsen et al., 2014). Furthermore, academy players who cover greater distances during the YoYo intermittent recovery test level 1 maintained performance to a greater extent during 7 x 30 m sprints interspersed by 25 s recovery than those with poorer high speed running ability (Chaouachi et al., 2010). High speed running capacity appears, in academy football players at least, to be related to repeated sprint ability (Gibson et al., 2013). What is less clear is how these qualities can be trained effectively amongst this demographic.

Table 2: Repeated sprint assessments employed with academy football players

Author	Age	Participants	Protocol	Recovery	Outcome measures
Aziz et al., 2007	16 – 18 years	53 national level elite players	6 x 20 m	20 s	Fastest sprint Total sprint time Percentage decrement
Aziz et al., 2008	15.4 ± 0.4 years	39 national level players	6 x 20 m	20 s	Fastest time Total sprint time
da Silva et al., 2010	19.9 ± 1.0 years	29 national level Brazilian players	7 x 43.2 sprints inc. change of direction	25 s	Fastest sprint Men sprint time Sprint decrement
Gibson et al., 2013	17.5 ± 1.2 years	32 players from an elite academy	6 x 40 m sprints inc. change of direction	25 s	Fastest sprint Total sprint time Percentage decrement
Huijgen et al., 2014	17 – 18 years	113 talented adolescent football players	3 x 30 m with 3 x 180^{o} change of direction per repetition	20 s	Fastest sprint Total sprint time
Ferrari Bravo et al., 2008	17.3 ± 0.5 years	15 elite adolescent players	6 x 40 m sprints inc. one 180^{o} change of direction	Sprints departing every 20 s	Fastest sprint Mean sprint time
Buchheit et al., 2010	14.5 ± 0.5 years	15 elite adolescent players	6 x 30 m sprints inc. one 180^{o} change of direction	Sprints departing every 20 s	Fastest sprint Mean sprint time
Haugen et al., 2015	17.0 ± 1.0 years	52 junior players	15 x 20 m	60 s	Best sprint Mean sprint time RPE

Ingebrigsten et al., 2013	16.9 ± 0.6 years	16 junior elite players	7 x 35 m	Sprints departing every 30 s	Mean sprint time Best sprint time
Tonnessen et al., 2011	16.4 ± 0.9	20 well trained elite young players	10 x 40 m	60 s	Mean sprint time
Barbero-Alvarez et al., 2013	14.3 ± 1.3	15 young players	7 x 30 m	Sprints departing every 30 s	Best sprint time Worst sprint time Men peak speed
Mujika et al., 2009	11 – 18 years	134 highly trained youth players	6 x 30 m	Sprints departing every 30 s	Total sprint time Percentage decrement
Chaouachi et al., 2010	19.0 ± 1.0 years	23 elite level players	7 x 30 m	25 s	Total sprint time Percentage decrement
Padulo et al., 2015	16.0 ± 0	17 outfield players – national standard	6 x 40 m inc. one change of direction	Three trials using 15, 20 and 25 s recovery	Best sprint time Worst sprint time Total sprint time

2.5 Growth, development and pacing strategies during high intensity exercise

2.5.1 Somatic growth and performance

Biological maturation can be quantified using invasive (Beunen & Malina, 1988; Malina, Coelho, Figueiredo, Carling, & Beunen, 2012; Tanner & Whitehouse, 1976) and non-invasive methods (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). The use of non-invasive methods may be more practical when working with large groups and their use has been well documented amongst academy footballers (Buchheit & Mendez-Villanueva, 2014b; McCunn et al., 2017; Mendez-Villanueva et al., 2010; Wrigley, Drust, Stratton, Atkinson, & Gregson, 2014) and have aided our understanding of how maturation affects physical qualities (McCunn et al., 2017). Early maturing boys perform better than their late maturing peers in measures of speed, power and strength; attributes that have a strong association with high speed running and repeated sprint ability (Gibson et al., 2013; Meckel et al., 2009; Mendez-Villanueva et al., 2011). The largest differences in these physical qualities occurs between 13 and 16 years of age, critical stages in the development of young football players (Malina et al., 2004; Philippaerts et al., 2006). Indeed, it is within this age range that maturation has the greatest effect on sprint speed over 15 m (McCunn et al., 2017). Whilst the increase in muscle mass and force production that occurs as a result of maturation facilitates improvement in measures of speed and strength (Philippaerts et al., 2006), it may also impair recovery between intense bouts of exercise (Ratel et al., 2003) given an increased reliance on glycolytic activity and greater activation of Type IIa, high force motor units (Ratel et al., 2003). It is well established that the ability to recover between high intensity efforts reduces through adolescence into adulthood (Ratel, Bedu, Hennegrave, Dore, & Duche, 2002; Ratel et al., 2003) whilst in parallel, increases in aerobic capacity that accompany the growth spurt (Malina et al., 2004; McNarry & Jones, 2014) may mitigate detrimental changes in fatigability during high intensity exercise with limited recovery (McNarry & Jones, 2014; Mendez-Villanueva et al., 2010).

These data highlight the importance of including some measure of biological maturation when assessing performance amongst academy football players in measures of physical capacity and movement characteristics during match play and training.

2.5.2 Assessing maturation

Individuals of the same chronological age can differ in stage, timing and tempo of biological maturation (Lloyd, Oliver, Faigenbaum, Myer, & De Ste Croix, 2014). Given that competitive leagues are structured according to chronological age, attempts have been made to control for differences in maturation through bio-banding, an approach that organises competition according to biological maturity (Mann & van Ginneken, 2017). Assessing maturation is important when interpreting measures of physical capacity (Wrigley et al., 2014), match performance (Buchheit & Mendez-Villanueva, 2014b) and the response to training (Lloyd et al., 2014) amongst academy football players.

Maturation can be quantified by assessing skeletal age (Beunen et al., 1992) and secondary sex characteristics known as Tanner staging, which has a strong association with skeletal age (Tanner & Whitehouse, 1976). These procedures, although valid and reliable (Beunen et al., 1992; Tanner & Whitehouse, 1976) present a logistical challenge when working with large groups of young athletes given the expertise and equipment required. Maturity offset, however, represents a non-invasive technique to assess biological maturation, calculated using anthropometry (Mirwald et al., 2002). Although this method has been used to assess maturation in academy footballers (Buchheit & Mendez-Villanueva, 2014b; McCunn et al., 2017; Selmi, Al-Haddabi, Yahmed, & Sassi, 2017) a poor relationship between maturity offset and skeletal muscle has been reported (Malina et al., 2012). Furthermore, maturity offset may be less accurate amongst late and early developers (Malina & Koziel, 2014). Despite this, in the field and applied setting maturity offset represents the best and most accessible means of assessing biological maturation.

2.5.3 Pacing strategies

Pacing strategies employed during athletic competition have been described as the efficient use of energetic resources, so that all available energy stores are used before finishing a race but not so far from the end that a meaningful reduction in speed occurs (Tucker & Noakes, 2009). Whilst this is true in endurance events there is an extra dimension in team sport that involves the effective allocation of recovery periods separating the frequent high speed efforts that occur (Bradley & Noakes, 2013). It is apparent from time motion analysis that during match play, recovery periods separating high speed efforts are not uniform in length (Buchheit, Mendez-villanueva, et al., 2010b). As such, young players must choose the most appropriate recovery duration based on perceived match demands and their ability to commence another high speed effort. If recovery periods are too short, there may be a reduction in the speed of subsequent efforts and/or fewer efforts in total; too long and the opportunity to make a meaningful contribution to the outcome of the game may be missed. Indeed, the fact that younger players appear to reduce the number of repeated sprint sequences as they become older and fitter suggests the development of a schema that allows them to more effectively match movement characteristics to the demands of the competition (Gastin, Fahrner, Meyer, Robinson, & Cook, 2013).

Pacing strategies identified in individual events include negative, positive, all out, even, parabolic and variable (Abbiss & Laursen, 2008). Changes in movement characteristic data in football have been described as positive or 'slow positive' (Waldron & Highton, 2014) evidenced by reductions in high speed running in the second half (Bradley et al., 2009; Mohr et al., 2005). Each half, however, displays a variability in movement characteristics, termed 'temporary fatigue' and characterised by transient reductions in running speed among academy football players (Hill, Sykes & Gibson, 2014). The complex interaction of tactics, opposition and physical capacity during match play, however, make establishing the cause of such transient reductions in running speed difficult. For example, are they responses to the environment, indicative of a pre-defined or responsive pacing strategy or a sign that the player is fatigued? Accordingly, there is value in investigating how academy footballers perform in the composite locomotor activities included in match play, high speed running and repeated sprinting, in a controlled environment under conditions where they are able to self-select appropriate running speeds and recovery intermissions.

2.5.4 Pacing strategies, growth and development

There is evidence to suggest that age and cognitive development play a role in identifying and implementing effective pacing strategies during exercise tasks that require the interpretation of temporal and spatial cues (Chinnasamy et al., 2013; Micklewright et al., 2012). This is important information for coaches and practitioners working with academy footballers, especially when conditioning practises such as high speed running are performed over set distances. Performing high speed running over set distances has been reported in the literature (Dupont et al., 2004; Ferrari Bravo et al., 2008) and is commonplace in the applied setting, along with repeated sprints (Taylor, Macpherson, Spears, & Weston, 2015). Despite widespread use no studies have investigated the fidelity of this approach in identifying how closely the movement characteristics adopted during high speed running and repeated sprinting over set distances match the speeds used in their prescription. Based on previous research using continuous rather than intermittent exercise it is possible that academy footballers may struggle to interpret the spatial cues necessary in the differentiation of sprinting and high intensity running activities (Chinnasamy et al., 2013). Although the use of high speed running has been shown to be efficacious in the development of physical qualities in academy football players (Faude et al., 2013; Ingebrigtsen et al., 2013; Tonnessen et al., 2011) a greater understanding of how closely actual movement characteristics match those used in their prescription may help optimise exercise prescription.

The use of externally regulated work to rest ratios in contemporary methods of training and testing academy football players, (high speed running and repeated sprinting with recovery periods prescribed *a priori)*, removes the requirement for players to interpret temporal cues; that is being responsible for selecting a recovery method appropriate for the aim of the session. Whilst the use of externally regulated work to rest ratios in testing (Krustrup et al., 2003) and training (Ingebrigtsen et al., 2013) provide a more stable stimulus by which to evaluate performance and the physiological responses that ensue, they may not be the most ecologically valid approach when considering the requirements of match play. During match play, academy football players adopt a variety of recovery durations separating repeated sprints, ranging from 15 to 20 s (Buchheit, Mendez-villanueva, et al., 2010b) likely in response to the changing match environment and perceptions relating to their ability to perform subsequent bouts of intense exercise. Indeed, when recovery durations of a similar magnitude to those observed in match play (15 s) were used in a repeated sprint protocol, performance was compromised (Balsom et al., 1992; Padulo et al., 2015) raising the question of whether academy players, during match play, are able to select recovery durations that do not compromise running performance.

During match play there is a gradual reduction in the number of repeated sprint sequences and those separated by the shortest recovery intervals (15 s) as players become chronologically older (Buchheit, Mendez-villanueva, et al., 2010b). This may suggest that as players become older and more experienced they become more adept at apportioning appropriate between effort recovery periods in environments in which they have autonomy over this variable. In controlled settings characterised by repeated sprints and high speed runs performed in series, adults have been shown to adopt a conservative approach to selecting recovery durations between these high intensity efforts so that performance is maintained (McEwan et al., 2018; Phillips et al., 2014). During repeated sprints on a cycle ergometer adult participants overestimated the amount of time required to maintain performance when self-selected between sprint recoveries were employed (Phillips et al., 2014). Similarly, trained runners performing high speed running on a non-motorised treadmill interspersed by self-selected recovery periods spent more time at or above the target speed than when externally regulated recovery periods were used (McEwan et al., 2018). Collectively, these data suggest that when adults self-select recovery intervals separating bouts of high intensity exercise they overestimate the time necessary to maintain performance. To date, no similar studies have been conducted in adolescent football players. Investigating how adolescent football players apportion recovery when able to self-select this variable under controlled conditions may aid our understanding of why, despite increases in fitness, the incidence of repeated sprint sequences during match play reduce as players become chronologically older (Buchheit, Mendez-villanueva, et al., 2010b).

2.6 Summary

High speed running and repeated sprinting are key components of match play, training and testing protocols within academy football settings. To date, however, the work to rest ratios used in testing and training practises have been externally regulated with recovery intervals established *a priori* which may not represent the way such activities are organised during match play. Furthermore, the biological and cognitive changes that occur during adolescence may impact on the appropriateness of such regimented work to rest ratios. To date there have been no studies investigating the fidelity of high intensity interval training in youth populations nor how performance is affected when intervals are interspersed by non-uniform recovery periods. Given the importance of high speed running and repeated sprinting to the development of academy football players further work in this area is warranted and necessary.

CHAPTER 3: GENERAL METHODS

3.1 Linear speed

All assessments of linear speed were completed on an indoor synthetic pitch with players permitted to wear their own football boots. After a warm up, players performed a 15 m maximal effort sprint with split timings at 5, 10 and 15 m from a standing start 0.5 m behind the first timing gate. Data were recorded using electronic timing gates (Smartspeed, Fusion Sport, Australia). Players received three attempts to record their fastest time over 15 m. The reliability of the 15 m sprints calculated as the typical error was 1.7%, measured as part of the normal practises employed for assessing the players at their club and validated at the national level through a programme of testing similarly aged players in performance schools. This equated to a Technical Error of Measurement of 0.4 s.

3.2 Repeated sprint assessments

Players performed 10 x 30 m maximal sprints interspersed by either 30 s externally regulated or self-selected recovery periods in Chapters 5 and 6. Before the self-selected trial players were instructed to "*allow the minimum amount of time to maintain a maximal effort in each sprint equal to their fastest single 30 m effort*", which was adapted from previous work (Glaister et al., 2010). There was no further instruction, encouragement or communication during the trial. All sprints were initiated from a standing start 0.5 m behind the first timing gate that marked the point at which players returned to after each effort. Sprint timings were recorded using electronic timing gates (Smartspeed, Fusion Sport, Australia) placed at zero and 30 m. Outcome variables of fastest sprint time, mean sprint time, total between sprint recovery time and percentage decrement (100 x (total sprint time/ideal sprint time)-100) were calculated afterward. These variables have been shown to be appropriate measures of repeated sprint performance (Glaister et al., 2010).

3.3 YoYo intermittent running assessments

YoYo assessments, with the exception of those conducted in Chapter 7, were performed on an indoor synthetic pitch. Running channels 20 m in length were marked with cones along with a 5 m recovery zone at one end. With running speeds governed by an audio signal, players ran backwards and forwards between the cones at increasing speeds until they were no longer able to keep time with the audio signal. Players were afforded two warnings for falling behind the required running speed before being removed from the assessment if a third warning was required. The final stage completed was used as their score with the corresponding speed and total distance recorded for analysis. During the YoYo intermittent endurance assessment players were afforded 5 s recovery between each 20 m shuttle. During the intermittent recovery version of the assessment, players were afforded 10 s of recovery between each 20 m shuttle. During each recovery period players were required to move around a cone placed 5 m behind the 20 m running track and return to the start line so that each new shuttle was commenced from a standing start.

The reliability of the YoYo intermittent endurance assessment calculated via the coefficient of variation has been reported to be 3.9% for elite youth footballers (Bradley et al., 2011). The reliability of the YoYo intermittent recovery assessment level 1 calculated via the coefficient of variation has been reported to range between 4.9 and 8.7% coefficient of variation (Bangsbo et al., 2008; Povoas et al., 2016).

3.4 Countermovement jump

Players performed a countermovement jump (CMJ) for assessment of both peak power (Watts) and flight time:contraction time ratio (F:C ratio; s) using a portable force platform (Force Platform, Ergotest Innovation, Porsgrunn, Norway) connected to a laptop (Dell Inspiron 9100, Dell, United Kingdom). Players performed two practice jumps before a third from which data were collected using commercially available software (MuscleLab 4020e, Ergotest Innovation). Players were instructed to flex their knees to approximately 120 degrees before jumping as high as possible with their hands remaining on their hips. The landing and take-off positions for jumps were assumed to be the same, with any jumps that deviated from the stated procedure ignored and an additional jump completed. The typical error established for flight:contraction time was 0.15 ± 0.07 s and 48.1 ± 38.4 W for peak power during data collection periods associated with this thesis.

3.5 Movement characteristics

Where applicable (Chapters 4 and 7), movement characteristics were measured using global positioning system devices (10 Hz Minimax X; Catapult Sports, Melbourne, Australia) worn in an appropriately sized vest and housed between the scapulae. Devices were activated outside and prior to being placed within the vest which participants wore with their training kit. A digital watch was synchronised with Greenwich Mean Time and used to record the start and end of the data collection period in each trial. These times were then used to truncate the raw GPS data files. All data were downloaded to a computer and analysed using appropriate software. This method provides a valid and reliable measurement of movement characteristics (Waldron, Worsfold, Twist, & Lamb, 2014). Analysis techniques were based on methods shown to be valid in previous research and appropriate for the population including PlayerLoad™ (Barrett et al., 2016) and individualised speed thresholds associated with the final speed recorded during the YYIRT1 (Buchheit et al., 2015). PlayerLoad™ was also recorded and has been shown to be reliable measure of musculoskeletal load with CV values ranging from 3.8 to 8.5% for during a protocol that simulates competitive match play (Barrett et al., 2016).

3.6 Biological maturation

Body mass, stature and seated stature were recorded for the assessment of biological maturity. These measures were familiar to the participants in all studies as they formed part of the battery of tests within their monthly monitoring fitness schedule. These data were subsequently used to calculate maturity offset (Mirwald et al., 2002). Age at peak height velocity, a somatic indicator of biological maturity which reflects the maximum velocity of growth in stature during adolescence, was used as a relative indicator of maturation (Mirwald et al., 2002). This method, when compared to the Bone Mineral Accrual study (Bailey, 1997) has shown a mean difference in boys of -0.01 years with a standard deviation of 0.49 years (Mirwald et al., 2002) and has been used in the assessment of academy footballers (McCunn et al., 2017).

3.7 Heart rate responses

For the measurement of heart rate players were fitted with a heart rate monitor positioned around the chest (Polar, Oy, Finland) prior to the commencement of exercise. The monitor was moistened prior to being fitted to aid in connectivity. Data were downloaded to a laptop using customised software (Polar Team, Oy, Finland) and analysed in custom built spreadsheets. The analysis of heart rate data included the calculation of training impulse

(TRIMP) as has been described elsewhere (Stagno, Thatcher, & van Someren, 2007), maximum heart rate, heart rate recovery and the time spent above 90% of maximum. Maximum heart rate was determined as the maximal heart rate achieved prior to volitional exhaustion in an intermittent running assessment and was used in Chapters 4 and 7. Heart rate recovery was defined as the beats per minute differential between the peak heart rate attained after each sprint during a repeated sprint assessment and at the recommencement of exercise in Chapters 5 and 6. This method has been used elsewhere to assess recovery in youth footballers (Buchheit et al., 2012).

3.8 Ratings of perceived exertion

The modified Borg CR10 scale (Foster et al., 2001) was used in Chapters 4, 5 and 6 to collect subjective indices of exertion immediately after exercise and where appropriate multiplied by the total time spent exercising to calculate a score of sessional RPE (sRPE). In Chapter 7 RPE values were recorded during exercise and so the 15 point Borg scale (Borg, 1982) was adopted as has been previously used in team sport players during shuttle-based running (Scott, Black, Quinn, & Coutts, 2013). All players were habituated with the relevant scales either through their regular use at the club post training or via specific sessions to familiarise them with their use. The reliability of RPE during high speed running has been reported to range from 4.0-6.0% coefficient of variation (Doherty et al., 2001)

3.9 Collection of blood lactate

In Chapter 4 whole blood capillary samples were obtained from the fingertip 60 s after the final repetition for the assessment of blood lactate concentration. Fingertips were sterilised using antiseptic wipes, cleaned and then punctured using disposable lancets. The first three drops of blood were wiped away to avoid contamination via the sterile wipe before a fourth was taken for analysis. Samples were refrigerated and analysed using a bench top system (Biosen C Line, Germany) within 30 min of collection. All samples were taken in a safe and clean environment adhering to guidelines stated in the BASES accredited laboratory in which they were analysed. The reliability of the benchtop analyser was calculated to be 0.42% TEM.

CHAPTER 4: Movement characteristics, physiological and perceptual responses of academy football players during and following acute exposure to high speed running and repeated sprinting.

Publications based on chapter 4 include:

Gibson, N., Henning, G., & Twist, C. (2018) Movement characteristics, physiological and perceptual responses of elite standard youth football players to different high intensity running drills. *Science and Medicine in Football* 2(4), 281-287.

4.1 INTRODUCTION

Physical qualities including speed (Mendez-Villanueva et al., 2011), agility (Dellal & Wong del, 2013) and aerobic capacity (Waldron & Murphy, 2013), are associated with successful football performance. Better aerobic capacity is associated with improved running performance in matches (Castagna et al., 2010) and accelerated recovery during repeated sprinting (Meckel et al., 2009). When performed chronically, aerobic capacity can be improved using high intensity interval training scheduled as high speed running (Faude et al., 2013) and repeated sprinting (Tonnessen et al., 2011). Little is known, however, about the movement characteristics, physiological and perceptual responses during individual training sessions of this nature in academy football players. A greater understanding of the responses to individual sessions may allow practitioners to periodise training load more effectively (Akubat et al., 2012) and identify why some players do not improve performance in measures of physical capacity despite exposure to training interventions (Faude et al., 2013).

Whilst training programmes involving repeated sprints and high speed runs are often scheduled using specific running speeds, little is known about how closely the actual movement characteristics of these approaches resemble those prescribed (Dupont et al., 2004; Haugen et al., 2014; Ingebrigtsen et al., 2013). In runs of this nature, and when performed in the field, participants are required, through the use of periods of acceleration, deceleration and constant speed running, to apportion their effort so to cover the prescribed distance in the allotted time. However, compared to adults, children are less able to interpret temporal cues which may compromise their ability to cover set distances in specific time periods (Chinnasamy et al., 2013). Investigating how accurately the movement characteristics of actual training reflect that detailed in its prescription among academy players for who this approach to training prescription is common in the applied environment warrants further investigation.

During training interventions, high speed running and repeated sprints have been scheduled in series. That is, repetitions of the same intensity, duration and type performed with uniform recovery in the same set (Dupont et al., 2004; Ferrari Bravo et al., 2008). Whilst this is an effective means of improving speed and aerobic capacity (Iaia et al., 2015; Tonnessen et al., 2011) it represents a uniform approach to training prescription that may not reflect the variety in locomotor activities representative of football specific training, match play (Buchheit, Mendez-Villanueva, et al., 2010a; Harley et al., 2010) and protocols designed to replicate match play (Nicholas, Nuttall, & Williams, 2000; Russell, Rees, Benton, & Kingsley, 2011). Using a training modality that alternates repeated sprints and high speed running might be an equally effective way of prescribing training of this nature whilst incorporating runs of differing intensities. However, to date, training prescription of this nature has not been reported in the literature.

The aim of the present study was to investigate the movement characteristics, physiological and perceptual responses of academy football players to three different high speed running drills matched for total distance and incorporating high speed running, repeated sprinting or a combination of the two. The research hypothesis for this chapter was as follows: 1) there would be differences in movement characteristics between those used to prescribe running drills and those which resulted from their execution; 2) physiological load would be higher in the high speed running trials as a result of shorter recovery periods and longer periods of running; 3) differences would exist in movement characteristics and internal load when high speed running and repeated sprinting were performed in sequence compared to in an alternate manner.

4.2 METHODS

4.2.1 Participants

Seventeen players (age: 14.9 ± 0.6 y; maturity offset 1.4 ± 0.7 y; stature: 173.2 ± 5.7 cm; body mass: 64.1 ± 7.1 kg; maximum HR 207 ± 7 b·min^{-1}) from the same professional football academy in their country's top tier of competition took part in the investigation that received ethics approval from Heriot-Watt University, School of Life Sciences and conformed to the recommendations of the Declaration of Helsinki. *Post-hoc* power analysis suggested a sample size of 18 participants were required to achieve a *large* effect based on data relating to heart rate derived TRIMP. All participants were accustomed to high intensity training and were engaged in approximately 9-12 hours of organised practice and one competitive fixture per week.

4.2.1 Design

Players performed three running conditions in a randomised order achieved by drawing conditions from a sealed box for each participant: 12 x 15 s high speed running at the speed corresponding to their final stage in the YoYo intermittent recovery test level 1 (YYIR1) (Buchheit et al., 2015) interspersed by 15 s recovery, 12 x ~4 s repeated sprints with ~26 s recovery and combination running comprising two repeated sprints followed by two high speed runs, as performed in their respective conditions. Six repetitions of each running modality in the combination condition were completed in total. During each condition participants completed the same total running distance, achieved by allocating individual 'running tracks' identical in length for each condition and equal to the distance associated with the high speed running condition. During repeated sprinting players were able to cover the remainder of the 'running track' following their sprint at an intensity that brought them to the opposite end in time to start the subsequent repetition. Each condition lasted six minutes and required players to start each new repetition at 30 s intervals. Sessions were performed at the same time and night of the week (either Tuesday, Wednesday or Friday), separated by six days and conducted on a synthetic pitch before normal squad training (ambient temperature: $12.3 \pm 1.2\ ^{o}C$; relative humidity: $65 \pm 3.1\%$; wind speed: 8.4 ± 3.6 km.h-1). All sessions were conducted in the month of March which was in the second half of the players' season; training recommenced for the second half of the season in January after a two week break over Christmas. Players were asked to maintain their normal pre-training nutrition practises during the study period and ensure that these were the same before each visit. Rating of perceived exertion (RPE) was collected at the end of each condition along with a fingertip blood sample to measure blood lactate concentration. Movement characteristics were measured using micro-technology and heart rate was recorded throughout to calculate training impulse (TRIMP) (Stagno et al., 2007). Countermovement jumps (CMJ) were performed before, 2 min and 14 hours after each condition.

4.2.3 Assessment of physical capacities

Assessments of physical capacity comprising the YYIR1 and 15 m linear sprint were performed one week before the first experimental condition. All assessments were completed in the early evening before normal squad training on a synthetic surface. Details of these assessments can be found in the General Methods chapter in sections 3.3 and 3.1 respectively.

4.2.4 Repeated sprint condition

Twelve maximal sprints were completed starting every 30 s. Players were instructed to sprint maximally from a stationary position until they were in line with a marker placed 30 m from the start line. Upon reaching the marker players were instructed to decelerate before making their way to a marker opposite the start line located at a distance equal to that in the high speed running condition (Figure 1). Players were able to select a locomotor activity they felt best allowed them to recover from the sprint whilst still being in place at the opposite end of the running track in time to start the next repetition; this involved a mix of jogging, walking and standing. A distance of 30 m was chosen as it represented a distance that would allow the calculation of speed over the initial 4 s period of each repetition, a sprint duration used in previous studies (Buchheit, Cormie, et al., 2009). The mean 30 m sprint time for this group of players was 4.71 ± 0.26 s. Participants were given verbal instruction to ‘get ready’ 10 and 5 s before starting each repetition.

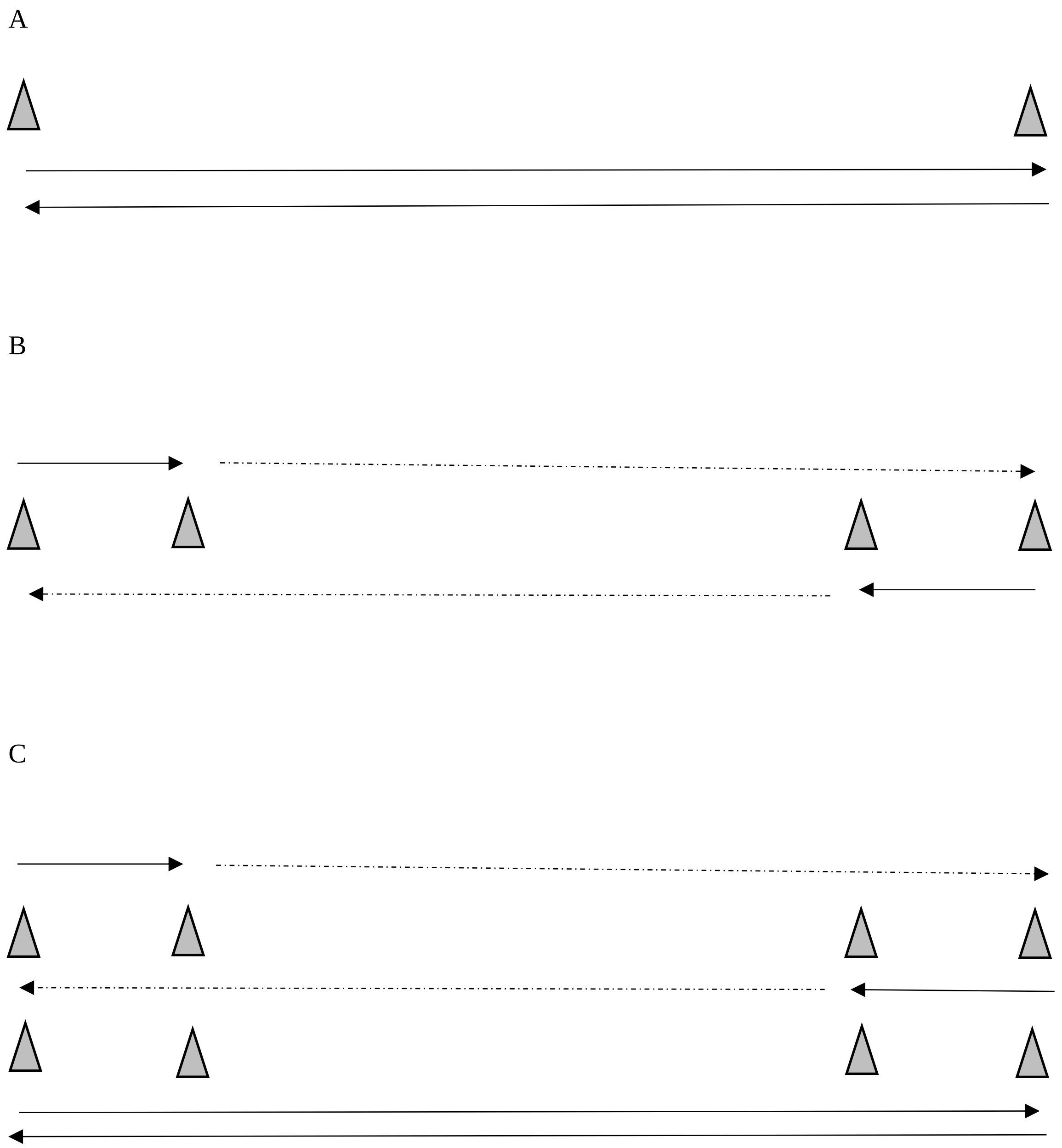


Figure 1: Individual running channel for high speed (A), repeated sprint (B) and combination running conditions (C). Solid black arrows denote either 30m sprints or high intensity runs, dashed black lines denote active recovery. Distance between triangular markers in A and C denotes that corresponding to the final speed achieved in the YYIRT1 covered in 15s.

4.2.5 High speed running condition

The running speed corresponding to the final stage achieved in the YYIR1 was converted to $km \cdot h^{-1}$ and used to calculate the distance of each 15 s repetition. Each player ran in their own allocated channel measured to within 0.5 m of the required distance. Repetitions started every 30 s and players were instructed to pace their running speed to arrive at the marker on, or as close as possible to the 15 s target. Passive rest was employed in the 15 s recovery period between intervals. During each shuttle players were given verbal feedback as to elapsed time at 5, 10 and 15 s and then 5 s before the start of the next repetition.

4.2.6 Combination running condition

This condition comprised two maximal sprints followed by two high intensity runs in an alternating pattern until 12 repetitions in total (6 sprints and 6 high intensity runs) had been completed. Each player ran in their own allocated channel with distances and associated feedback for sprint and high speed running repetitions identical to that described above.

4.2.7 Measurement of movement characteristics

Details of the procedures for the collection of movement characteristics are provided in the General Methods chapter, section 3.5.

4.2.8 Measurement of internal load

Details of the procedures for the collection of internal load data including heart rate, RPE and blood lactate are provided in the General Methods chapter, sections 3.7, 3.8 and 3.9 respectively.

4.2.9 Countermovement jump performance

Details relating to the collection of countermovement hump data are presented in the General Methods chapter, section 3.4.

4.2.10 Statistical analysis

Effect sizes (ES), ± confidence limits, relative change (in percentages) expressed as the transformed (natural logarithm) ± 90% confidence limits, and magnitude-based inferences were calculated for all physiological and performance outcome measures. Effect sizes were defined as: *trivial* = 0.2; *small* = 0.21–0.6; *moderate* = 0.61–1.2; *large* = 1.21–1.99; *very large* > 2.0 (Batterham & Hopkins, 2006). Threshold probabilities for a substantial effect based on the 90% confidence limits were <0.5% most unlikely, 0.5-5% very unlikely, 5-25% unlikely, 25-75% possibly, 75-95% likely, 95-99.5% very likely, and >99.5% most likely (Batterham & Hopkins, 2006). Magnitude based inferences were only reported for probabilities greater than 75%, all other comparisons used effect size thresholds. Thresholds for the magnitude of the observed change for each variable were determined as the between participant SD x 0.2, 0.6 and 1.2 for small, moderate and large effect, respectively (Batterham & Hopkins, 2006). Effects with confidence limits across a likely small positive or negative change were classified as unclear. For those wishing to interpret the analysis using a more traditional approach, p-values based on appropriate null hypothesis tests are also included using SPSS (SPSS Inc, Chicago, IL, USA).

4.3 RESULTS

4.3.1 Assessments of physical capacity

The mean speed during the maximal 15 s sprint assessment (6.28 ± 0.2 $m \cdot s^{-1}$) was *most likely* (21.6%; ES 7.65 ± 1.02; P = 0.001) faster than the speed associated with the final level completed during the YYIR1 (4.9 ± 0.4 $m \cdot s^{-1}$). There were small differences in sprint speeds during the repeated sprint condition (6.4 ± 0.4 $m \cdot s^{-1}$) (2.5%; ES 0.31 ± 0.4; P = 0.08) and those recorded in the linear sprint assessment, suggesting that players were sprinting maximally.

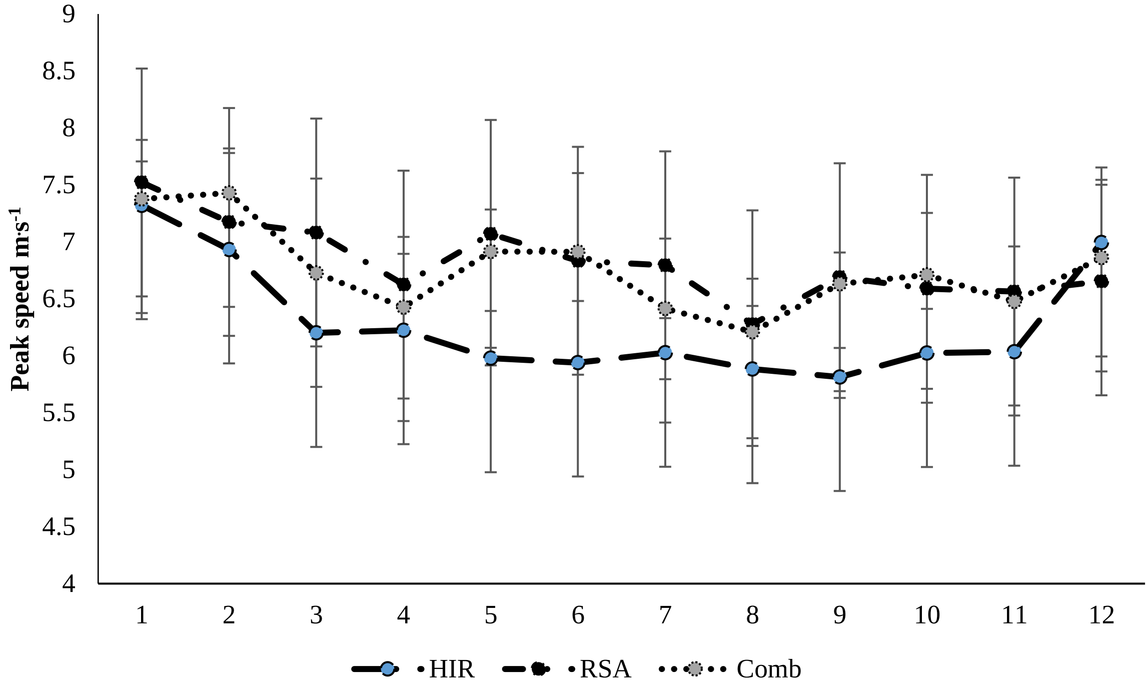
4.3.2 Movement characteristics

Movement characteristics for each condition are presented in Table 3 Figures 2A and 2B and Figures 3A and 3B. There were small differences in peak speed achieved in combination running (1.1%; ES 0.23 ± 0.44; P 0.42) compared to high speed running. All other comparisons for peak speed were trivial. Small differences in mean speed over the initial 4 s of each repetition were observed in repeated sprinting (6.2%; ES 0.44 ± 0.51; P = 0.11) and combination running (6.3%; ES 0.45 ± 0.46; P = 0.13) compared to high speed running, respectively. Differences between the repeated sprint and combination running condition were trivial. Time at or above maximal sprint speed was *likely higher* in combination running when compared to the high speed running (39.8%; ES 0.9 ± 0.7; P = 0.04) and repeated sprinting (28.5%; ES 0.91 ± 0.83; P = 0.05), respectively. Differences between repeated sprint and high speed running conditions were trivial. Time at or above the speed associated with the final stage of the YYIR1 was *most likely higher* during high speed running compared to repeated sprinting (51.8%; ES 3.6 ± 0.58; $P = 0.001$) and combination running (25%; ES 1.38 ± 0.44; $P < 0.001$). Time above the speed associated with the final stage of the YYIR1 was *most likely* higher in the combination running when compared to repeated sprinting (35.7%; ES 2.12 ± 0.4; $P = 0.001$).

Speeds associated with repeated sprint and high speed running repetitions performed in series and in an alternate pattern are presented in Figures 3 and 4. There were trivial differences in peak speed during maximal sprint repetitions within the repeated sprint condition (6.9 ± 0.3 $m \cdot s^{-1}$) and corresponding repetitions (1-2, 5-6, 9-10) in the combination running condition (7.0 ± 0.3 $m \cdot s^{-1}$). Mean speed over the first 4 s of each repetition was *very likely* slower (7.7%; ES 1.15 ± 0.82; $P = 0.02$) in the repeated sprint (5.0 ± 0.4 $m \cdot s^{-1}$) compared to corresponding repetitions (1-2, 5-6, 9-10) in the combination running condition (5.3 ± 0.3 $m \cdot s^{-1}$).

Likely faster (4.6%; ES 0.76 ± 0.66; $P = 0.03$) peak speeds were observed during high speed running repetitions (3-4,7-8,11-12) in the combination (6.5 ± 0.4 $m \cdot s^{-1}$) compared to high intensity running condition (6.2 ± 0.3 $m \cdot s^{-1}$). Mean speed over the first 4 s of each repetition was *likely faster* (-4.7%; ES -0.31 ± 0.44; $P = 0.03$) during high speed running (5.4 ± 0.5 $m \cdot s^{-1}$) compared to corresponding repetitions (3-4,7-8,11-12) in the combination running condition (4.9 ± 0.3 $m \cdot s^{-1}$).

A



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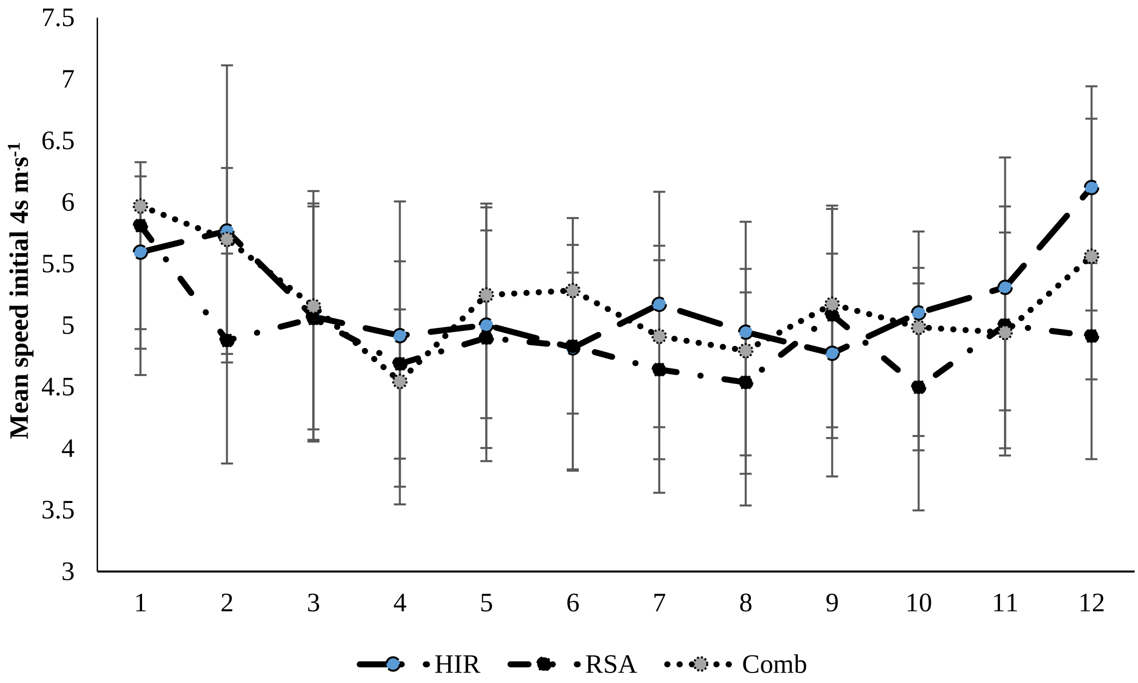
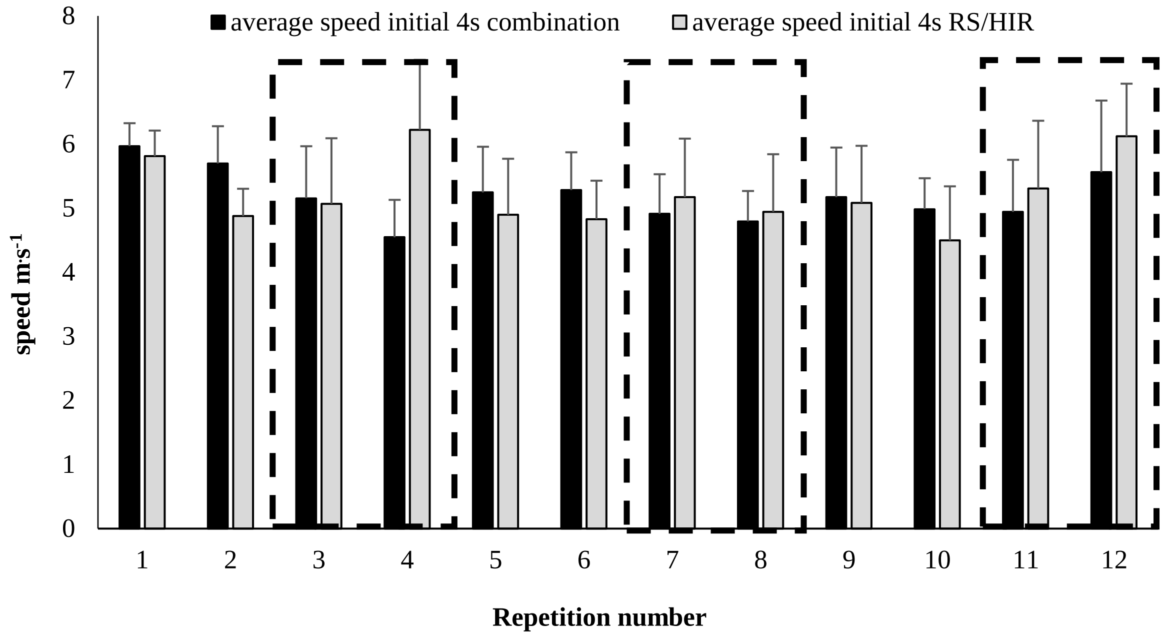


Figure 2: A (upper) and B (lower): Movement characteristics associated with each repetition of high speed running, repeated sprinting and combination running for (a) peak speed and (b) mean speed over the initial 4 s.

A



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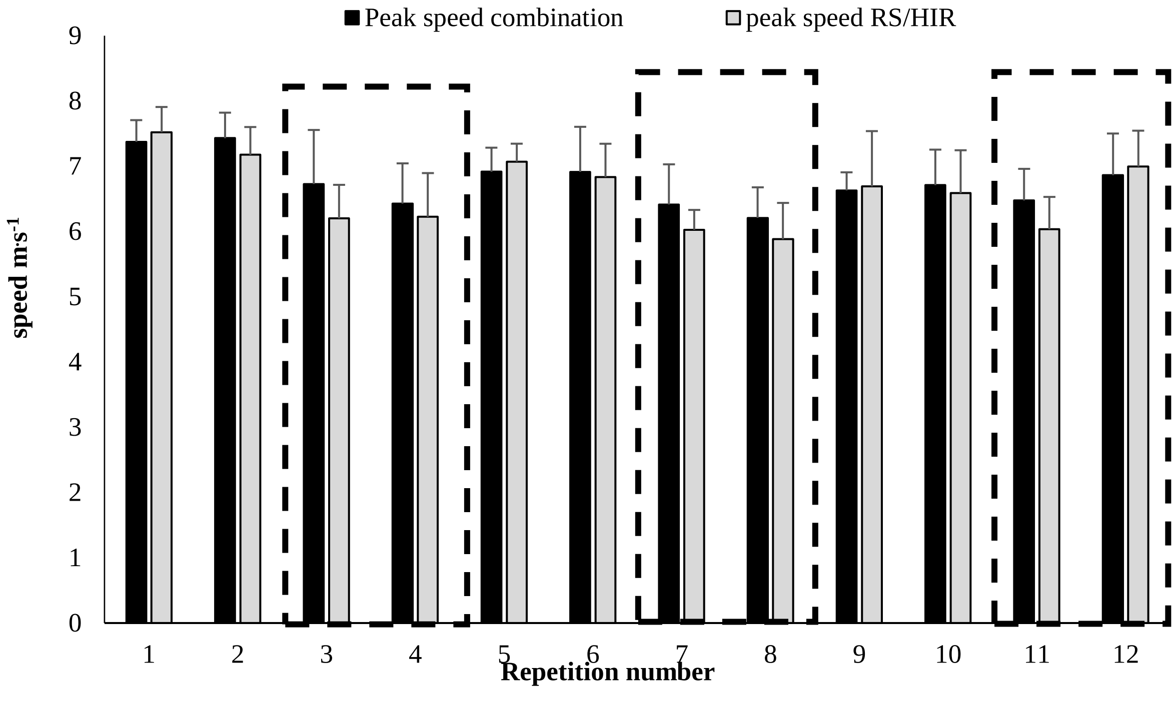


Figure 3: A (upper) and B (lower): Comparison of mean speeds over the initial 4 s (a) and peak speeds (b) in each repetition in the combination running condition and corresponding repetition in the repeated sprint and high speed running conditions. High speed running repetitions are denoted by the dashed line.

4.3.3 PlayerLoad^{TM}

There were moderate differences in PlayerLoad^{TM} (4.8%; ES 0.62 ± 0.82; P = 0.27) during repeated sprints compared to high speed running. When compared to combination running differences were trivial. PlayerLoad^{TM} was *likely higher* in the combination compared to the high intensity running condition (5.3%; 0.68 ± 0.9; P = 0.27).

4.3.4 Internal responses to high speed running drills

There was a small difference in RPE (8.5%; ES 0.26 ± 0.48; P = 0.38) after high speed running compared to repeated sprinting and combination running (3.4%; ES 0.1 ± 0.35, P = 0.52. All other comparisons were trivial. There was a trivial difference in blood lactate following combination compared to repeated sprint running (3.4%; ES 0.1 ± 0.32; P = 0.38). A. There was a small difference in TRIMP (49.4%; ES 0.27 ± 0.24; P = 0.31) during repeated sprinting compared to high speed running and combination running (9.4%; ES 0.06 ± 0.12; P = 0.34). Small differences in TRIMP (36.3%; ES 0.21 ± 0.41; P = 0.84) were observed during combination compared to high speed running. Internal response data are presented in Table 4.

4.3.5 Countermovement jump performance

Small differences were observed in F:C at 2 min after the high intensity (-2.6%; ES -0.19 ± 0.46; P = 0.47) and combination running (-2.5%; ES -0.27 ± 0.29; P = 0.29) conditions. There were trivial differences following repeated sprinting (-2.0%; ES -0.15 ± 0.33; P = 0.57) reductions at the same time point. At 14 hours there were *likely* reductions in F:C ratio after high speed (-5.6%; ES –0.44 ± 0.32; P = 0.01) and combination running (-6.8%; ES -0.53 ± 0.47; P = 0.07). Changes in the repeated sprinting condition were trivial.

There were small differences in the F: C ratio immediately post repeated sprint and high speed running (1.5%; ES 0.07 ± 0.33; P = 0.84) and (4.5%; ES 0.21 ± 0.41; P = 0.27) following combination running. There were small differences in F:C ratio after combination running when compared to high speed running (6.7%; ES 0.3 ± 0.38; P = 0.17).

There were small differences in F:C ratio (3.7%; ES 0.23 ± 0.41; P = 0.84) following high speed running and combination running (4.7%; ES 0.3 ± 0.58; P = 0.38) compared to repeated sprinting at 14 hours post completion. There were trivial differences between high speed running and combination running.

Table 3: Peak speed, mean speed during the initial 4 s of each repetition and time above maximal sprint speed and the final YYIR1 speed during high speed running, repeated sprints and combination running conditions. Target exercise time was calculated as the number of repetitions multiplied by either 15 s or 4 s for high intensity running and repeated sprints, respectively.

	High speed running	Repeated sprinting	Combination running
Peak speed ($m \cdot s^{-1}$)	7.6 ± 0.34	7.63 ± 0.34	7.68 ± 0.5
Mean speed over initial 4 s ($m \cdot s^{-1}$)	4.9 ± 0.59	5.22 ± 0.74	5.19 ± 0.4
Time above final YYIR1 speed (s)	38.43 ± 7.2	18.5 ± 3.1	28.7 ± 4.3
Time above maximal sprint speed (s)	10.33 ± 5.06	9.55 ± 2.88	14.2 ± 6.26
Target exercise time (s)	180	~48	~114

Table 4: Rating of perceived exertion, blood lactate, PlayerLoad™, modified TRIMP and flight:contraction time after high intensity running, repeated sprinting and combination running conditions.

	High speed running	Repeated sprints	Combination running
RPE	5.9 ± 1.7	6.3 ± 1.4	6.1 ± 1.3
Blood lactate ($mmol \cdot l^{-1}$)	10 ± 2.8	9.6 ± 1.9	9.3 ± 2.5
Modified TRIMP (AU)	43.2 ± 16.2	48.6 ± 12.7	44.2 ± 10.8
PlayerLoad™ (AU)	279.2 ± 39.1	291.6 ± 21.4	293 ± 23.1
Flight:Contraction time (s)			
Baseline	0.76 ± 0.01	0.77 ± 0.1	0.75 ± 0.1
2 min post	0.79 ± 0.12	0.78 ± 0.15	0.74 ± 0.12
14 hours post	0.73 ± 0.13	0.75 ± 0.12	0.72 ± 0.14

4.4 DISCUSSION

Despite *most likely* differences in the speeds used to prescribe high speed and repeated sprint running intervals, the observed movement characteristics along with PlayerLoad^{TM}, perceptual and physiological responses were of a smaller magnitude. These data would suggest that where the aim of high speed running prescription is to maximise time spent at or above the target speed, practitioners may consider using intervals in excess of 15 s to give players more opportunity to achieve and maintain the intended pace (Macpherson & Weston, 2015). Performing repeated sprints and high speed running intervals in an alternate pattern rather than in series altered the movement characteristics associated with each. These data suggest that interspersing high speed running and repeated sprints in the same set may facilitate peak speed during high intensity runs but be harmful to mean speed over the initial 4 s of repeated sprints.

When peak speeds were compared during the combination running condition differences of a trivial nature were reported for repeated sprint repetitions whilst high speed running repetitions were *likely* faster than in the high intensity running condition. Mean speed over the initial 4 s was facilitated in the combination condition for repeated sprint repetitions yet detrimental to high speed running repetitions. Collectively these data suggest that combination running allows increases in peak speed for high speed running and mean speed over the initial 4 s of repetitions during repeated sprints. Indeed, prior dynamic activity can improve sprint speed in football players when incorporated into warm up routines (Gelen, 2010). Further research is required to assess whether alternating runs of varying intensity within the same set is a useful means of using high intensity interval training to enhance physical capacity when prescribed longitudinally (Tonnessen et al., 2011). However, practitioners should be aware of the *likely* slower mean speed over the initial 4 s during high speed running intervals. These data highlight the need for practitioners to assess on a session by session basis the movement characteristics performed by players and how closely these reflect those which were prescribed in relation to the intended aim.

Higher peak speeds achieved in combination compared to high speed running may explain why PlayerLoad™ values were *likely* higher in the former whilst only small differences existed compared to repeated sprinting. Indeed, higher PlayerLoad™ has been reported during striding compared to sprinting during a football simulation protocol (Barreira et al., 2017). Although the validity of whole body loading assessed using global positioning technology has been questioned (Nedergaard et al., 2017), the metric may be useful when prescribing training for academy players at different stages of their physical development. The increased mechanical load associated with combination running may be an unwanted outcome, especially given the paucity of information surrounding appropriate loading patterns for young athletes (Gabbett, Whyte, Hartwig, Wescombe, & Naughton, 2014; van der Sluis et al., 2014).

There were moderate differences in individualised TRIMP values during repeated sprinting when compared to high speed running. Although the duration of high intensity activity was less during repeated sprinting compared to high speed running (4 s cf. 15 s) participants were required to cover the same total distance using locomotor activities that ensured they arrived at the opposite end of the running track in time to start the next repetition. Active recovery of this nature can enhance the rate at which metabolic waste products are removed (Dupont & Berthoin, 2004) which may explain the similarity in blood lactate response in the present study. Despite reducing specific metabolites produced during exercise, active recovery interspersing high speed running can increase heart rate (Buchheit, Cormie, et al., 2009) because of a greater exercise intensity. Whilst this may be beneficial in maximising time at $VO_{2\ max}$, it could be detrimental during repeated sprinting where the aim is to maintain speed (Thevenet, Tardieu-Berger, Berthoin, & Prioux, 2007), and could explain higher TRIMP values during repeated sprinting. Furthermore, given the relationship between RPE and the physiological responses to intermittent exercise (Foster et al., 2001; Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004), a higher TRIMP during repeated sprinting might explain the differences reported in RPE after the condition compared to high speed running.

The volume of high speed running players undertake during a season is dependent on the number of matches they contest, with fringe players performing less than regular starters (Anderson et al., 2016). This is perhaps the result of fringe players following a similar loading pattern as starters yet without the stimulus of high speed running achieved during matches. *Likely* reductions in F:C from pre to 14 hours after high intensity and combination running were detected, whilst changes after repeated sprinting at the same time point were *unclear*. These data suggest that high intensity training in the form of repeated sprinting and high speed running, if performed the day before might impair neuromuscular function during match play, especially as changes in running efficiency have been linked to the F:C ratio (Cormack et al., 2013).

4.5 CONCLUSION

High speed running and repeated sprinting achieve similar physiological and perceptual responses in academy football players despite being prescribed using different target speeds. Academy players appear to alter their approach to high intensity running and repeated sprints when they are alternated within the same set. Therefore, scheduling training of this nature may promote faster running speeds during high intensity repetitions yet be detrimental during repeated sprint efforts. Neuromuscular function was recovered 14 hours after repeated sprinting and may be important in the scheduling of such activity within the weekly microcycle.

4.6 PRACTICAL APPLICATIONS

Academy football players engage in both high speed running and repeated sprinting during competitive match play (Harley et al., 2010) and, as such, should train both qualities. When physiological responses and movement characteristics are considered, both running modalities elicit similar acute responses. Performing repeated sprinting and high speed running in an alternate pattern, rather than in series, facilitates faster speeds during the latter and as such could be a useful stimulus for developing this physical component. In instances where the aim is to limit mechanical load, for example during periods of rapid growth or when returning from injury, high intensity running performed in series yielded the lowest values for PlayerLoad™. Coaches and practitioners should consider assessing the fidelity of training practices that required youth players to cover a predetermined distance in a specific time to ensure what is performed in terms of movement characteristics corresponds with what was prescribed and intended. This is especially important where such practices are intended to maximise time spent at or above a specific running speed threshold.

CHAPTER 5: Physiological, perceptual and performance responses associated with self-selected versus externally regulated recovery periods during a repeated sprint protocol in academy football players.

Publications based on chapter 5 include:

Gibson, N., Brownstein, C., Ball, D., & Twist, C. (2018) Physiological, perceptual and performance responses associated with self-selected versus standardised recovery periods during a repeated sprint protocol in elite youth football players: A preliminary study. *Pediatric Exercise Science* 29(2); 186-193.

5.1 INTRODUCTION

Repeated sprint protocols that employ externally regulated work to rest ratios have been studied in youth footballers (Barbero-Álvarez et al., 2013; Padulo et al., 2015) and are related to the physical demands of match play (Barbero-Álvarez et al., 2013). This notwithstanding, published data suggests that repeated sprint protocols use a greater number of sprints and longer recovery durations than those observed in competitive match play in both youth (Buchheit, Mendez-villanueva, et al., 2010b) and adult populations (Carling et al., 2012).

Repeated sprint performance is affected by the length of recovery period afforded between efforts (Balsom et al., 1992; Padulo et al., 2015). For example, recovery duration during 6 x 40 m sprints was inversely related to the rate of fatigue and blood lactate concentration after exercise, possibly through an increased physiological load and exercise-induced acidosis (Padulo et al., 2015). Despite the evidence suggesting that short recovery periods are detrimental to performance in repeated sprint sequences, repeated sprint sequences with equally short between effort intermissions have been reported during match play (Buchheit, Mendez-villanueva, et al., 2010b). Whilst acknowledgeing that external factors will influence between effort recovery intermissions during match play, players are able to self-select these periods, and based on movement characteristic data (Buchheit, Mendez-villanueva, et al., 2010b), select reovery perods similar to those that result in impaired performance in repeated sprint protocols. Adopting self-selected recovery periods during repeated sprint protocols might therefore present a way of assessing athletes that more closely resembles the non-unform recovery periods evident during match play (Buchheit, Mendez-villanueva, et al., 2010b).

Repeated sprint tasks utilsing self-selected recovery periods have ben examined in adults who demonstrate different physiological responses when compared to children. For example, peak blood lactate concentration after repeated and single sprints is lower in boys compared to men (Engel et al., 2015), a difference in part explained by reduced release from the active musculature (Ratel et al., 2002) and a lower body mass (Ratel et al., 2003). Children also exhibit an enhanced ability to preserve performance across multiple sprints with shorter recovery periods than in adults (Ratel et al., 2002). These data support the notion that children rely predominantly on aerobic energy provision, even during high intensity exercise (Armstrong & Welsman, 2001; Ratel et al., 2003). Given the difference in how adults and chidlren respond to high intensity exercise, the adoption of work to rest ratios designed for adults might overestimate the time required to recover between sprints when performed by younger populations.

Repeated sprint exercise provides an effective stimulus for enhacing aerobic capacity in young footballers (Faude et al., 2013; Tonnessen et al., 2011). Individulaising the intensity of activity bouts has been advocated during sport specific high-intensity aerobic training (Helgerud et al., 2007) and linear running drills (Dupont et al., 2004). However, as yet, the inidividualisation of recovery periods for repeated sprint practises has yet to be explored. Allowing young players to select their own between-sprint recovery periods might enable individualisation of this variable such that physiological responses are optimised for different training outcomes.

Accordingly, the aim of the current empiracal study is to determine the physiological, perceptual and performance outcomes associated with a repeated sprint assessment in academy footballers using both self-selected and externally regulated between sprint recovery periods. The research hypothesis for this study was as follows: differnces would exist in the between sprint recovery intermissions when externally regulated and self selected and that these differences woud impact on performance outcomes and physiological load.

5.2 METHODS

5.2.1 Participants

Eleven male footballers (age 13.7 ± 1.1 years; 0.1 ± 1.3 years from peak height velocity [PHV] (Mirwald et al., 2002); stature 164.8 ± 11.5 cm; body mass 52.9 ±16.2 kg) from the same professional academy and competing in the top tier of their country's competition volunteered to take part in the investigation. *Post-hoc* power analysis suggested a sample size of 18 participants to acheve a *large* effect based on recovery duration in the self-selected trial. Written informed consent was obtained from the participants and their legal guardians before data collection. All players had been involved in regular and organised training for at least 12 months with weekly sessions comprising three technical, two conditioning and one competitive match totalling ~10 hours per week. The study received institutional ethics approval from Heriot-Watt University and all procedures conformed to the Declaration of Helsinki.

5.2.2 Design

Using a randomised crossover design achieved by blinded selection of conditions from a box for each player, players completed two repeated sprint protocols with either self-selected or externally regulated between sprint recovery periods. In both conditions players completed the sprints in isolation to eliminate the potential for peer influence. Measures of neuromuscular function were obtained before and after each protocol along with measures of heart rate, rating of perceived exertion and blood lactate concentration. Both conditions were performed in the early evening (ambient temperature: 14.8 ± 2.8^{o}C; relative humidity: 71 ± 6.8%; wind speed: 11.4 ± 5.2 km·h^{-1}) before normal squad training on either a Tuesday or Wednesday on an artificial synthetic surface with six days between each condition. Data collection took place in September and October in the first half of the players' season.

5.2.3 Countermovement jump performance

For details on how countermovement jump data were collected refer to the General Methods chapter, section 3.4.

5.2.4 Repeated sprint protocol

For details relating to the assessment of repeated sprint ability refer to the General Methods, section 3.2.

5.2.5 Measurement of internal responses

For details regarding how heart rate, RPE and blood lactate were collected refer to the General Methods sections 3.7, 3.8 and 3.9 respectively.

5.2.6 Statistical analysis

Effect sizes (ES), ± 90% confidence limits, relative change (in percentages) expressed as the transformed (natural logarithm) and magnitude based inferences were also calculated for all physiological and performance outcome measures. Effect sizes were defined as: *trivial* = 0.2; *small* = 0.21–0.6; *moderate* = 0.61–1.2; *large* = 1.21–1.99; *very large* > 2.0 (Hopkins, Marshall, Batterham, & Hanin, 2009). Threshold probabilities for a substantial effect based on the 90% confidence limits were <0.5% *most unlikely*, 0.5-5% *very unlikely*, 5-25% *unlikely*, 25-75% *possibly*, 75-95% *likely*, 95-99.5% *very likely*, and >99.5% *most likely*. Magnitude based inferences were only reported for probabilities greater than 75%, for differences that did not reach this threshold the effect size was reported. Thresholds for the magnitude of the observed change for each variable were determined as the between participant SD x 0.2, 0.6 and 1.2 for a small, moderate and large effect, respectively. Effects with confidence limits across a likely small positive or negative change were classified as *unclear* (Hopkins et al., 2009). For those wishing to interpret the analysis using a more traditional approach, p-values based on appropriate null hypothesis tests are also included using SPSS (SPSS Inc, Chicago, IL, USA).

5.3 RESULTS

5.3.1 Repeated sprint performance

The externally regulated recovery trial was *most likely (*43.1%; ES 1.64 ± 0.89; P = 0.001) longer in duration (2.3%; ES 0.4 ± 0.3; P = 0.03) and with *most likely* (57.7%; ES 1.55 ± 0.5; P = 0.001) greater total recovery time compared to the self-selected recovery condition. There were small differences in the fastest (1.4%; ES 0.23 ± 0.21; P = 0.06) and average (2.3%; ES 0.4 ± 0.29; P = 0.02) sprint times in the self-selected recovery trial compared to externally regulated whilst percentage decrement was *most likely* (65%; 0.36 ± 0.21; P = 0.12) lower in the externally regulated recovery trial (Table 5). Individual responses for percentage decrement and fastest sprint time are shown in Figures 5A and B with average recovery duration and sprint speed in the self-selected recovery condition and sprint times for both conditions in Figure 6A and B.

Comparisons between sprint speed during repetitions 2-10 and the initial sprint in the externally regulated recovery condition were all trivial (ES < 0.12; P = 0.57 - 0.99). There were small differences in the self-selected recovery trial when comparing sprint one with; sprints 2 and 6 (sprint 2, 1%; ES 0.19 ± 0.29; P = 0.25; sprint 5 1.5%; ES 0.29 ± 0.48; P = 0.28). Sprints 3, 4, 7 and 9 were *likely* slower (sprint 3, 3.1%; ES 0.59 ± 0.35; P = 0.1; sprint 4, 2.4%; ES 0.46 ± 0.37; P = 0.04; sprint 7, 3.2%; ES 0.6 ± 0.62; P = 0.09; sprint 9, 3.0%; ES 0.56 ± 0.59; P = 0.09) whilst sprint 5 was *very likely* slower (4.4%; ES 0.83 ± 0.42; P =0.005). Comparisons between sprint 1 and sprints 8 and 10 were trivial.

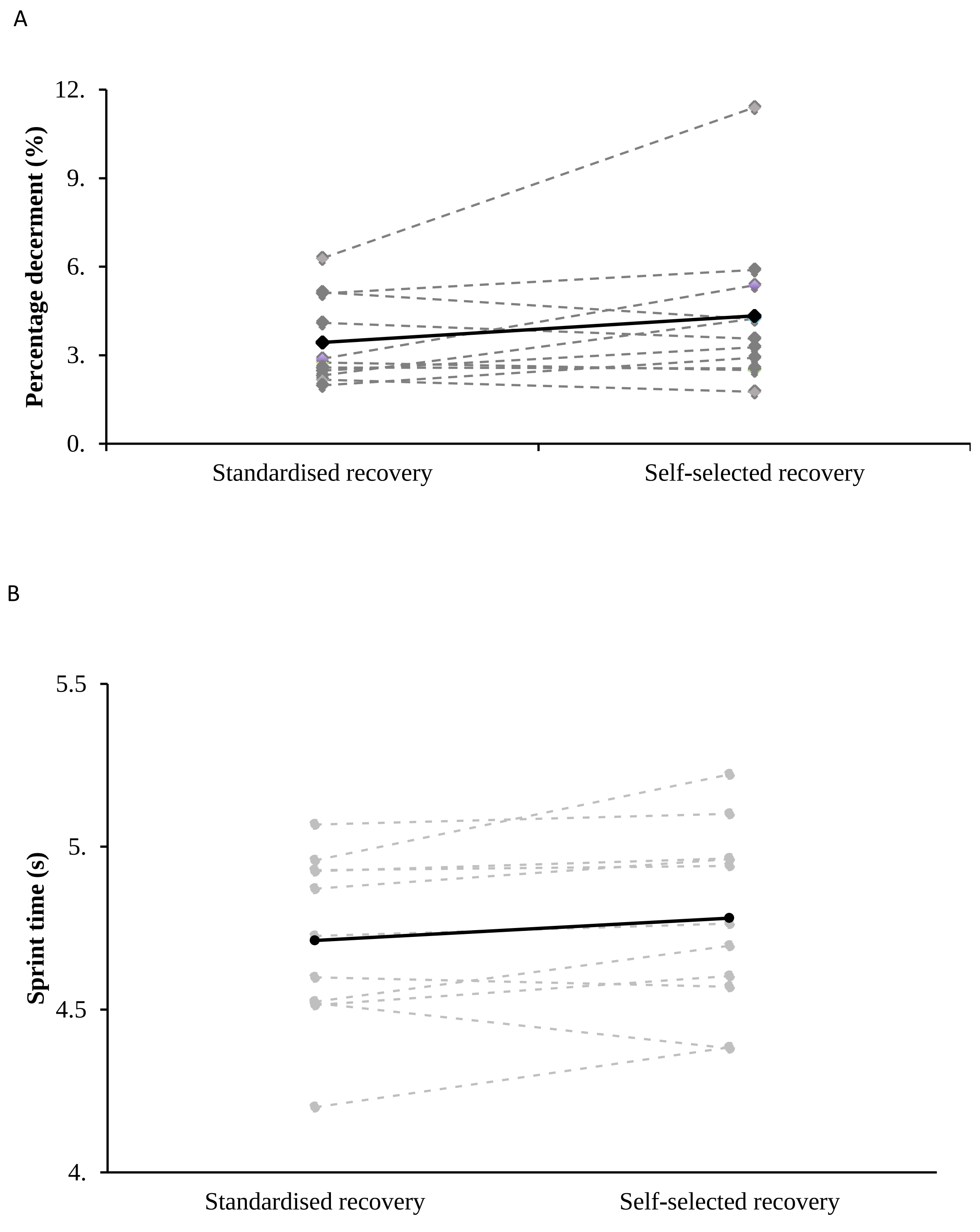
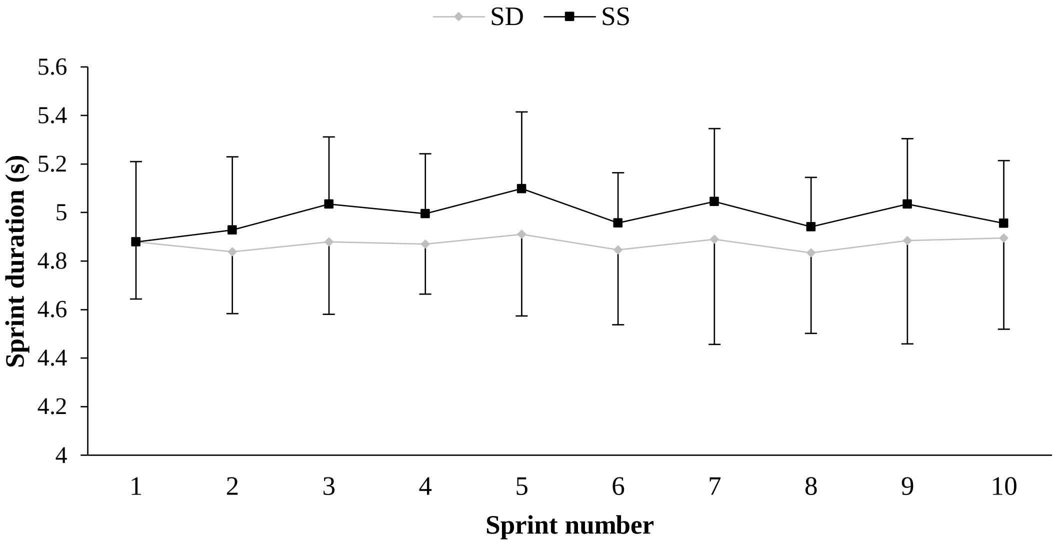


Figure 5: A (upper) and B (lower): Individual responses in percentage decrement (a) and fastest sprint (b) after externally regulated and self-selected recovery conditions.

5.3.2 Variability in self-selected recovery periods

There were small differences in the duration of between sprint recovery when compared to the first intermission for recovery periods 2, 8 and 9 (recovery 2, 13.9%; ES 0.36 ± 0.42; P = 0.841; recovery 8, 18%; ES 0.45 ± 0.47; P = 0.21; recovery 9, 15.9%; ES 0.4 ± 0.65; P = 0.27), *likely* longer for recovery periods 4, 6 and 7 (recovery 4, 17.9%; ES 0.45 ± 0.35; P = 0.09; recovery 6, 24.3%; ES 0.59 ± 0.44; P = 0.04; recovery 7, 27.7%; ES 0.67 ± 0.44; P = 0.03) and *very likely* longer for recovery 5 (26.2%; ES 0.63 ± 0.31; P = 0.01). There were trivial differences between recovery periods 1 and 3.

A



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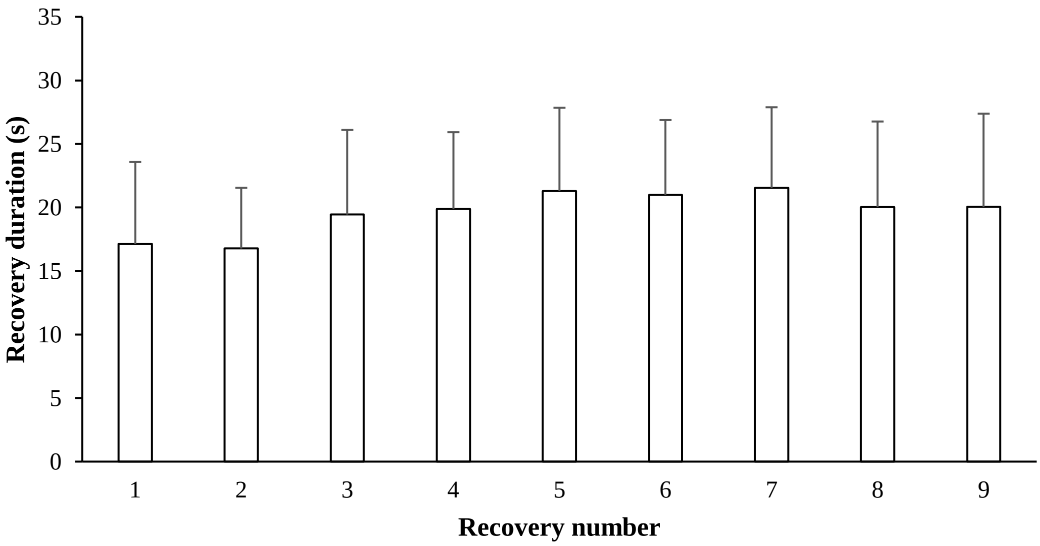


Figure 6: A (upper) and B (lower): Sprint durations during externally regulated (SD) and self-selected (SS) recovery trials (a) and between sprint recovery durations during the self-selected recovery trial (b).

5.3.4 Internal responses

Between sprint heart rate recovery was *very likely* (-58.9%; ES -1.10 ± 0.72; P = 0.05) lower with small differences in peak heart rate (1.8%; ES 0.24 ± 0.4; P = 0.001) in the self-selected compared to the externally regulated recovery condition. Blood lactate concentration was *likely* higher following the self-selected compared to the externally regulated recovery condition at 2 (21.5%; ES 0.9 ± 0.7; Δ 1.82 $mmol^{-1}$; P = 0.08), 5 (24.6%; ES 0.51 ± 0.35; Δ 1.25 $mmol^{-1}$; *P* = 0.02) and 7 minutes (18.3%; ES 0.58 ± 0.41; Δ 1.14 $mmol^{-1}$; P = 0.04). All comparisons for RPE were trivial (Table 5).

5.3.5 Countermovement jump performance

There were trivial differences in lower body power from pre to post-assessment (1268.8 ± 408.4 cf. 1308.6 ± 458.3 W; 2.1%; ES = 0.06 ± 0.09; *P* = 0.12) in the externally regulated and self-selected recovery trial (1285.5 ± 385.7 cf. 1299.5 ± 396.7 W; 0.7%; ES 0.02 ± 0.07; P = 0.53) respectively. Trivial differences were observed (-2.6%; ES -0.07 ± 0.12; P = 0.33) in post exercise lower body power between externally regulated and self-selected recovery conditions (Table 5).

Table 5: Repeated sprint performance and internal load responses for externally regulated and self-selected recovery duration conditions. Values are mean ± SD.

	Externally regulated recovery	Self-selected recovery
Total duration (min)	5.31± 0.04	3.78 ± 0.8
Total sprint duration (s)	48.73 ± 2.55	49.9 ± 3.0
Average recovery duration (s)	30.0 ± 0.0	19.7 ± 5.6
Fastest sprint (s)	4.71 ± 0.3	4.78 ± 0.3
Mean sprint time (s)	4.87 ± 0.3	4.98 ± 0.3
Percentage decrement (%)	3.4 ± 1.5	4.3 ± 2.7
Internal load responses		
Peak heart rate ($b \cdot min^{-1}$)	180 ± 12	183 ± 10
Recovery heart rate ($b \cdot min^{1}$)	9 ± 6	4 ± 4
RPE (6-20).	12.8 ± 1.	12.8 ± 1.7
Blood lactate conc. ($mmol \cdot l^{-1}$)		
2 min	7.05 ± 2.2	8.87 ± 2.6
5 min	5.93 ± 2.1	7.18 ± 2.1
7 min	6.04 ± 1.6	7.18 ± 2.0
Lower body power – 2 min post final sprint (W)	1308.6 ± 458.3	1299.5 ± 396.7

5.4 DISCUSSION

Data presented in this chapter show differences between conditions in line with the research hypothesis. This study compared the phsyiological and perceptual responses to a repeated sprint assessment that used both self-selected and externally regulated recovery periods in academy footballers. Fastest and average sprint speeds were slower whilst percentage decrement was *most likely* higher in the self-selected compared to the externally regulated recovery condition. There were *likely* lower magnitudes of heart rate reovery, higher peak heart rate and *very likely* higher blood lactate concentration in the self-selected reovery condition suggesting a higher physiological load when players were allowed to choose between sprint recovery intermissions.

Key performance determinants of repeated sprint ability are high sprinting speeds and fatigue resistance (Glaister et al., 2010) which the data presented herein would suggest are likely compromised when self-selected recovery periods are used by academy footballers. The performance decrements in the self-selected recovery condition can be attributed, in part, to the allocation of shorter between sprint intermissions. When allowed to self-select between sprint intermissions adults allocate longer recovery periods than would be employed in protocols with the same number of sprint repetitions and distances under externally regulated conditions (Phillips et al., 2014). Our findings with academy footballer players are therefore in contrast to those reported in adults. Despite having autonomy over between sprint recovery duration, players were unable to maintain sprint performance by effectively. With the exception of sprint six, the sprint time during repetitions three to seven were *likely* or *very likely* slower than sprint one in the self-selected rcovery condition. Despite this, players did not begin to allocate longer recovery periods, when compared to the first intermission, until after sprint four when performance had already begun to deteriorate. In this sense the player could be described to have adopted a reactive rather than prospective strategy to recovery allocation.

Running performance has previously been reported to be impaired when schoochildren paced their effort on a target time compared to distance (Chinnasamy et al., 2013). It has therefore been propsoed that children struggle to interpret the interaction between space, distance and time until the formal intelligence phase of their cognitive development occurs, which is between 14 and 18 years of age (Piaget, 1954). Given the age and stage of maturation in the present study (age 13.7 ± 1.1 years; 0.1 ± 1.3 years from peak height velocity), it is plausible that they may not have acquired the ability to prospectively regulate recovery duration in line with the demands of the assessment given the temporal rather than spatial nature of the task. As cognitive development was not measured in the present study, further work is required to understand how this variable might affect performance in tasks requiring the regulation of recovery duration.

Blood lactate concentration was higher at 2, 5 and 7 min after the self-selected recovery trial, and, given slower sprint times is likely the result of shorter between sprint recovery intermissions. Disturbances in metabolic homeostatis have been found to increase supraspinal fatigue by inhibiting central drive and afferent feedback signals from the active musculature (Goodall, Charlton, Howatson, & Thomas, 2015). The central mechanism hypothesis might explain the reduced sprint time and increased percentage decrement in the self-selected recovery trial. To date, studies investigating self-selected recovery periods have used adult participants and not reported blood lactate concentrations (Edwards, Bentley, Mann, & Seaholme, 2011; Glaister et al., 2010; Phillips et al., 2014), making comparisons with the current data difficult. Children have been shown to produce less lactate than their adult counterparts in short high intensity intermittent tasks (Engel et al., 2015; Ratel et al., 2002). Therefore, where elevated acidosis and an elevated physiological load is an intended outcome (Iaia et al., 2015), our data suggest that self-selected recovery periods might be warranted.

Higher peak heart rate values and a *very likely* reduced magnitude of heart rate recovery were observed in the self-selected compared to externally regulated recovery trial. When viewed in combintaion with a *likely* higher percentage decrement in the self-selected recovery trial, heart rate recovery seems an inappropriate method for assessing readiness to recommence short term, high intensity repeated sprint exercise in academy footballers (Edwards et al., 2011).

Despite differences in heart rate and blood lactate concentrations, RPE values differed only trivially between trials. The relationship between RPE, HR and blood lactate has been established in intermittent activities (Foster et al., 2001; Impellizzeri et al., 2004), with evidence to suggest that increases in the physiological response elevates perceptions of effort. However, our results support those presented in chapter four that during repeated sprint and high intensity running activities of a short but high nitensity nature, RPE might not be sensitive, in academy footballers at least, to changes in performance and physiological load.

Although there were *likely* differences in running performance and internal load between conditions, only trivial differences in countermovement jump performance were detected. These findings are consistent with those reported for academy football players following a training micro cycle with significant variations in running distance and the speeds at which locomotor activites were performed (Malone et al., 2015). The greater propensity for aerobic metabolism and lower absolute work during high intensity exercise in children, along with a reduced muscle mass when compared to adults (Ratel et al., 2003), might explain why lower body power was unaffected in this investigation and also in chapter four. Collectively, the results of chapters four and five support the assertion that field based measures of neuromuscular function are unable to identify small yet potentially meaningful changes in the force generating capacity of the lower body musculature in academy footballers (Malone et al., 2015). This observation is particulalry relevant since reductions in maximal voluntary force were detected after only two sprints when using laboratory methods to detect central and peripheral fatige albeit in adults involved in intermittent sports inclduing Association Football (Goodall et al., 2015).

While the benefits of individualising exercise intensity are well understood, externally regulated recovery periods are still commonly employed in applied and research environments. In the current study five participants demonstrated a lower percentage decrement in the self-selected recovery condition. Of these five participants, two recorded between sprint recovery periods in excess of 30 s (five recovery intermissions above 30 s, maximum of 36 s and two intermissions above 30 s, maximum of 33 s) while two participants performed their fastest sprint in the self-selected recovery protocol. Accordingly, these data suggest that externally regulated between sprint recovery periods might not always be the most effective way of programming repeated sprint exercise where the aim is to increase physiological load or when assessing this ability among youth athletes.

5.5 CONCLUSION

Peak and mean sprint speed along with percentage decrement during a repeated sprint task are likely compromised by the use of self-selected between effort recovery periods in academy footballers. The decrements in performance were accompanied by higher blood lactate concentration after exercise, higher peak heart rate and a lower magnitude of between sprint heart rate recovery. Trivial differences between trials were reported for RPE and countermovement jump performance. Where the aim of repeated sprint training is to maintain performance across each repetition, self-selected between sprint recoveries are not advised in academy footballers. Self-selected recovery periods might provide, however, a useful alternative to externally regulated rest periods for certain individuals and where the intention of scheduling this type of exercise is to increase physiological load.

5.6 PRACTICAL APPLICATIONS

This is the first study to compare performance during repeated sprints separated by either self-selected or externally regulated recovery periods in academy football players. Our results suggest that whilst performance is likely compromised with the use of self-selected recovery, some individuals might perform better under these conditions. This data should make coaches and practitioners cautious about how they interpret data resulting from repeated sprint tests, especially in light of research suggesting repeated sprinting to be a training aid rather than valid assessment protocol (Taylor et al., 2016) Furthermore, self-selected recovery periods induced *likely* increases in physiological load that might be advantageous when using repeated sprinting as a tool to condition players (Faude et al., 2013; Iaia et al., 2015). Further research should focus on how cognitive development and physical maturation impact on the ability of academy footballers to self-pace their activities during intermittent high intensity exercise.

CHAPTER 6: Biological maturation and its effect on repeated sprinting using externally regulated and self-selected recovery periods in academy football players.

Publications based on chapter 6 include:

Brownstein, C., Ball, D., Micklewright, D. & Gibson, N. (2018). The effect of maturation on performance during repeated sprints with self-selected versus standardised recovery intervals in youth footballers

6.1 INTRODUCTION

Repeated sprints are an effective and time efficient method of conditioning team sport athletes (Taylor et al., 2015). Studies investigating the use of repeated sprints on peformance, recovery, and metabolic response have attempted to optimise the training stimulus by varying work to rest ratios (Little & Williams, 2007), number of sprints (Gharbi et al., 2014; Taylor et al., 2015) and recovery modality (Castagna et al., 2008). However, an important consideration that is often overlooked when implementing repeated sprint training is the individual differences in the capacity to recover berween sprints, with research to date primarily employing externally regulated and pre-determined recovery durations (Buchheit, Mendez-Villanueva, Delhomel, et al., 2010; Castagna et al., 2008; Gharbi et al., 2014; Padulo et al., 2015). As recovery between sprints is largely driven by aerobic processes, it follows that individual differences in oxidative capacity will influence the duration required to recover in order to produce and reproduce sprint performance. As such, using an externally regulated, pre-determined approach to recovery intervals during repeated sprint training might not account for these individual differences and this could be a contributing factor in the varying outcomes and degree of effectiveness training programmes using repeated sprints have been shown to have at the indiviual level (Faude et al., 2013).

The issue of individual differences in the recovery between sprints is particulalry pertinent in young athletes, where the phsyiological responses to repeated sprints can be influenced by stage of biological maturation (Ratel, Williams, et al., 2006). Specifcially, prepubescent children have been shown to fatigue less during high intensity exercise and recover more quickly compared with post-pubescent adolescents (Armstrong & Welsman, 2001; Ratel, Williams, et al., 2006). Differences in the fatigue response are mediated by physiological, neuromuscular, and morphological changes that accompany the adolecent growth spurt (Ratel, Duche, & Williams, 2006). Indeed, variability in the association between repeated sprint performance and other measures of physical capacity have been reported in youth football players (Spencer et al., 2011). It has been suggested that enhanced aerobic capacity improves repeated sprint ability through improved recovery between sprints, however this has not been reflected in studies investigating the relationship between these two qualities in adolescent football players (Gibson et al., 2013; Pyne, Saunders, Montgomery, Hewitt, & Sheehan, 2008; Spencer et al., 2011). Indeed, it was suggested that to counter this, repeated sprint tests protocols should reflect the specific physiological demands of the sports they are being used to assess performance in or test players for (Spencer et al., 2011). As a result, using the same between sprint intermission for those at different stages of maturation may overestimate or underestimate recovery requirements, potentially compromising training adaptations. This issue is particularly relevant considering the groups of young academy footballers who often train with those of the same chronological age rather than biological maturity, meaning that variation in physiological responses to repeated sprints may exist within age groups around which biological maturation occurs.

An alternative approach that could address individual and maturational differences in fatigue susceptibiliy during repeated sprints is to allow participants to self-select between sprint recovery intervals. This appraoch has been applied in adult populations, with studies finding that adults could successfully maintain sprint performance when self-selecting recovery intervals (Glaister et al., 2010; Phillips et al., 2014). In a younger population, however, data from Chapter 5 has shown that performance was compromised, evidenced by slower sprint times and higher percentage decerements when self-selected recovery was used compared to that observed using externally regulated and pre-defined work to rest ratios during a repeated sprint task in academy footballers. However, in Chapter 5 individual responses were not uniform, with two participants displaying enhanced performance when using self-selected recovery intervals. This suggests that for some, self-selecting recoveries allows them to achieve a lower and thefore ‘better’ percentage decrement a measure often reported to coaches after asessments of repeated sprint ability. In Chapter 5, it was proposed that differences in the maturity level of the players could have been a mitigating factor in the variable results found, and was suggested as an area for further research.

Self-selecting the duration of between-sprint recovery periods requires athletes to interpret their readiness to recommence sprinting in the context of the task and based on their perception of exertion and perceived state of recovery. The self-monitoring process requires complex cognition relating to temporal cues, planning, anticipation, and logical reasoning (Eston, 2009). Previous work has suggested that the ability to self-regulate exercise intensity is influenced by intellectual functioning (Van Biesen, Hettinga, McCulloch, & Vanlandewijck, 2016). Furthermore, it has been reported that children at an earlier stage of cognitive developemnt were less able to evenly regulate exercise intensity during a 450 to 900 m track run compared to those at a more advanced stage of cognitive development (Micklewright et al., 2012). Given there are likely to be differences in cognitive and intellectual development between academy footballers at different stages of biological maturation, it is possible that the ability to self-regulate between-sprint recovery intervals may be compromsied in those less mature. Thus, although using self-selected recovery intervals has the potential to account for differences in fatigue susceptibility, given the cognitive demands associated with self-selected recovery intervals, it is unclear whether this approach is suitable for academy footballers at different stages of biological maturation. Understanding the applicability of repeated sprints with self-selected recovery can provide important information for practitioners working with young players at varying stages of maturation.

The aim of the present empiracal study was to assess the effect of maturation status on performance during repeated sprints separated by self-selected recovery compared with externally regulated recovery intervals in academy footballers at different stages of biological maturation. The research hypotesis stated that less mature players would allocate less recovery between sprints which would result in greater decerments in performance and higher physiological load when compared to their more mature peers.

6.2 METHODS

6.2.1 Participants

Participants were recruited using quota sampling, whereby random samples were recruited from the age groups of interest until an appropriate number of participants had been reached. A total of 28 male academy football players (n = 14 pre peak height velocity [PHV] and n = 14 post PHV) across three different age groups (under 13, 14 and 15) from the same professional football academy took part in the study. Post-hoc sample size calculation identified 24 participants were required for the identification of a *large* effect based on recovery duration in the self-selected recovery trial. Descriptive data for the two groups can be found in Table 6. Participants were habituated with repeated sprint exercise and trained four times per week (average total training time per week ~ 360 min) in addition to at least one competitive match per week in the year preceding the study. Each participant was informed of the study procedures; players and their guardian(s) gave informed written consent prior to data collection. The study received institutional ethics approval from Heriot-Watt University and conformed to the Declaration of Helsinki.

Table 6: Descriptive characteristics of participants in the pre [n = 14] and post [n = 14] PHV groups.

	Pre-PHV group (n = 14)	Post-PHV group (n = 14)
Age (years)	12.7 ± 0.45	14.4 ± 0.45
Stature (cm)	153.7 ± 7.1	170.9 ± 6.6
Seated stature (cm)	119.9 ± 3.5	129.9 ± 3.7
Body mass (kg)	41.2 ± 6.8	59.5 ± 11.3
Maturity offset (y)	-1.24 ± 0.5	0.91 ± 0.7

6.2.2 Design

A between-group repeated-measures design was used. Before data collection, quota sampling was used to identify and recruit 14 participants who were either pre or post PHV. Players were recruited from the under 13, under 14 and under 15 age groups. These age groups were chosen since they span the ages at which PHV most commonly occurs based on historical data from the same academy and research to date (Mirwald et al., 2002). Consequently, when performing training in groups based on year of birth, as if often the case in Association Football, there is likely to be considerable variation in biological maturity, which in turn could influence fatigue susceptibility and recovery during bouts of repeated sprints. Each player was asked to perform 10 x 30 m sprints under two conditions; one with a 30 s externally regulated recovery period and another where the individual self-selected between sprint recovery duration. In all trials sprints were conducted individually to eliminate the influence of peer influence. Trials were conducted in a randomised order with each condition blindly selected for pre-PHV players and the post-PHV following the opposite order, with one week between conditions. Data were collected on either a Tuesday or Wednesday evening prior to normal squad training and was conducted on an indoor synthetic pitch during the second half of the players season (March-April) and following a two week intermission in training for Christmas.

6.2.3 Maturity offset

For information relating to how maturity offset was calculated refer to the General Methods chapter, section 3.6.

6.2.4 Repeated sprint test

For information relating to the assessment of repeated sprint ability with and without self-selected recoveries, refer to the General Methods chapter, section 3.2.

6.2.5 Statistical analysis

Effect sizes (ES), ± 90% confidence limits, relative change (in percentages) expressed as the transformed (natural logarithm) and magnitude based inferences were also calculated for all physiological and performance outcome measures. Effect sizes were defined as: *trivial* = 0.2; *small* = 0.21–0.6; *moderate* = 0.61–1.2; *large* = 1.21–1.99; *very large* > 2.0 (Hopkins et al., 2009). Threshold probabilities for a substantial effect based on the 90% confidence limits were <0.5% *most unlikely*, 0.5-5% *very unlikely*, 5-25% *unlikely*, 25-75% *possibly*, 75-95% *likely*, 95-99.5% *very likely*, and >99.5% *most likely*. Only probabilities greater than 75% were reported, for differences less than this threshold effect size was reported. Thresholds for the magnitude of the observed change for each variable were determined as the between participant SD x 0.2, 0.6 and 1.2 for a small, moderate and large effect, respectively. Effects with confidence limits across a likely small positive or negative change were classified as *unclear* (Hopkins et al., 2009). For those wishing to interpret the analysis using a more traditional approach, p-values based on appropriate null hypothesis tests are also included using SPSS (SPSS Inc, Chicago, IL, USA).

6.3 RESULTS

6.3.1 Between-group analysis of physical characteristics

Age (12.7%; ES 3.21 ± 0.51; P = 0.001), body mass (43.8%; ES 2.55 ± 0.66; P = 0.001), stature (11.3%; ES 2.20 ± 0.56; P = 0.010), seated stature (8.3%; ES 2.51 ± 0.59; P = 0.001) and maturity offset (34.6%; ES 4.85 ± 0.93; P = 0.02) were all *most likely* different between the pre and post PHV groups.

6.3.2 Between-group analysis

Performance and physiological data for between group comparisons in the externally regulated and self-selected recovery trials are presented in Table 7. In the self-selected recovery trial, mean recovery duration was *likely* (P = 0.16) lower in the pre-PHV compared with the post-PHV group. Percentage sprint decrement was *likely* (P = 0.03) lower in the pre compared to post-PHV group during the externally regulated recovery trial and was *likely* (P = 0.02) higher in the pre compared with post-PHV group during the self-selected recovery trial. Mean sprint times were *most likely* shorter in the post compared to pre PHV groups during externally regulated (P = 0.001) and self-selected recovery trials (P = 0.001). Fastest sprint times were also *most likely* faster in the post compared to pre PHV groups during the externally regulated (P = 0.001) and self-selected recovery trial (P = 0.01). There were small differences in mean HR (P = 0.07) and peak HR (P = 0.04) between pre- and post-PHV groups in the externally regulated trial. There were trivial differences between mean and peak HR in the self-selected recovery trial. Average sprint times are displayed in Figures 8A and B whilst average recovery duration in the self-selected condition for pre and post PHV groups are detailed in Figure 9.

Table 7: Performance and physiological responses to 10 x 30 m repeated sprint exercise with 30 s externally regulated and self-selected recovery intervals in the pre- and post-peak-height-velocity group. Between group differences expressed as percentage change and effect sizes with 90% confidence intervals.

	Externally regulated recovery		Between group % difference; ES ± 90% CI	Self-selected recovery		Between group % difference; ES ± 90% CI
	Pre-PHV	Post-PHV		Pre-PHV	Post-PHV	
Fastest sprint (s)	4.9 ± 0.2	4.6 ± 0.3	8.3 ± 3.8%; ES 1.47 ± 0.52	5.0 ± 0.2	4.7 ± 0.2	6.1 ± 3.8%; ES 1.27 ± 0.57
Mean sprint (s)	5.1 ± 0.2	4.8 ± 0.2	7.0 ± 2.9%; ES 1.54 ± 0.54	5.2 ± 0.2	4.9 ± 0.2	7.8 ± 2.8%; ES 1.56 ± 0.54
Sprint decrement (%)	2.1 ± 1.1	3.2 ± 2.1	37 ± 44.4%; ES 0.41 ± 0.51	5.8 ± 3.52	4.4 ± 3.8	50 ± 56.4%; ES 0.45 ± 0.54
Mean recovery time (s)	30.0 ± 0.0	30.0 ± 0.0		17.8 ± 7.4	21.6 ± 6.6	26.1 ± 16.6%; ES 0.62 ± 0.71
Mean HR ($b \cdot min^{-1}$)	163 ± 11	167 ± 10	2.5 ± 4.7%; ES 0.37 ± 0.63	172 ± 8	171 ± 10	0.6 ± 2.9%; ES 0.09 ± 0.60
Peak HR ($b \cdot min^{-1}$)	174 ± 9	179 ± 8	3.2 ± 4.1%; ES 0.56 ± 0.51	188 ± 10	187 ± 7	0.2 ± 2.1%; ES 0.10 ± 0.47

6.3.3 Within-group analysis pre-PHV group

Physiological and performance data are displayed in Table 7, while average sprint times for the pre-PHV group for externally regulated and self-selected recovery trials are displayed in Figure 6A and B. Mean sprint duration was *likely* (3.0%; ES = 0.78 ± 0.46; P = 0.01) shorter in the externally regulated recovery trial compared to the self-selected recovery trial while no trivial differences(0.5%; ES = 0.13 ± 0.5; P = 0.66) existed for fastest sprint time. Percentage sprint decrement was *most likely* (60.1%; ES = 1.38 ± 0.71; P = 0.001) lower during the externally regulated compared to self-selected recovery trial. Mean recovery duration was *most likely* (84.6%; ES 1.23 ± 0.45; P = 0.001) longer in the externally regulated compared with self-selected recovery trial. Mean HR was *very likely* (5.4%; ES 1.06 ± 0.65; P = 0.02) lower and peak HR *most likely* (5.2%; ES = 0.98 ± 0.41; P = 0.02) lower in the externally regulated compared with the self-selected recovery trial.

There were trivial differences between times recorded for sprint two and the initial sprint during the self-selected recovery trial (0.7%; ES 0.18 ± 0.22; P = 0.16); magnitudes for all other comparisons were, *most likely* for sprints three (3.7%; ES 0.95 ± 0.29; P = 0.001), five (5.8%; ES 1.48 ± 0.54; P = 0.001), seven (6.7%; 1.69 ± 0.65; P = 0.01) and nine (6.7%; ES 1.68 ± 0.74; P = 0.02), and *very likely* for sprints four (3.3%; ES 0.84 ± 0.43; P = 0.04), six (5.0%; ES 1.28 ± 0.64; P = 0.04), eight (5.1%; ES 1.3 ± 0.74; P = 0.01) and ten (5.3%; ES 1.34 ± 0.83; P = 0.01). For the externally regulated recovery trial trivial and small differences were reported between the initial sprint and sprints two (0.6%; ES 0.2 ± 0.54; P = 0.51), three (0.9%; ES 0.33 ± 0.35; P = 0.12), four (0.3%; ES 0.11 ± 0.38; P = 0.58), six (0.4%; ES 0.14 ± 0.47; P = 0.02), eight (0.5%; ES 0.16 ± 0.21; P = 0.19), nine (1.0%; ES 0.36 ± 0.21; P = 0.01) and ten (0.4%;

ES 0.14 ± 0.34; P = 0.5). The magnitude of change between the initial sprint and repetitions five (1.4%; ES 0.5 ± 0.26; P = 0.04) and seven (1.3%; ES 0.45 ± 0.33; P = 0.03) were *likely*.

There were trivial differences in the length of recovery intermission compared to the first for intermission two (3.5%; ES 0.06 ± 0.13; P = 0.18) and three (23%; ES 0.35 ± 0.19; P = 0.01). The magnitude of difference for all other intermissions were *likely* (29.9%; ES 0.45 ± 0.21; P = 0.04) for intermission four, *most likely* for intermissions five (44.1%; ES 0.62 ± 0.18; P = 0.001) and seven (56%; ES 0.76 ± 0.23; P = 0.001) and *very likely* for intermissions six (37.4%; ES 0.54 ± 0.18; P = 0.001), eight (45.3%; ES 0.64 ± 0.28; P = 0.02) and nine (53.4%; ES 0.73 ± 0.28; P = 0.001) when compared to the initial between sprint intermission.

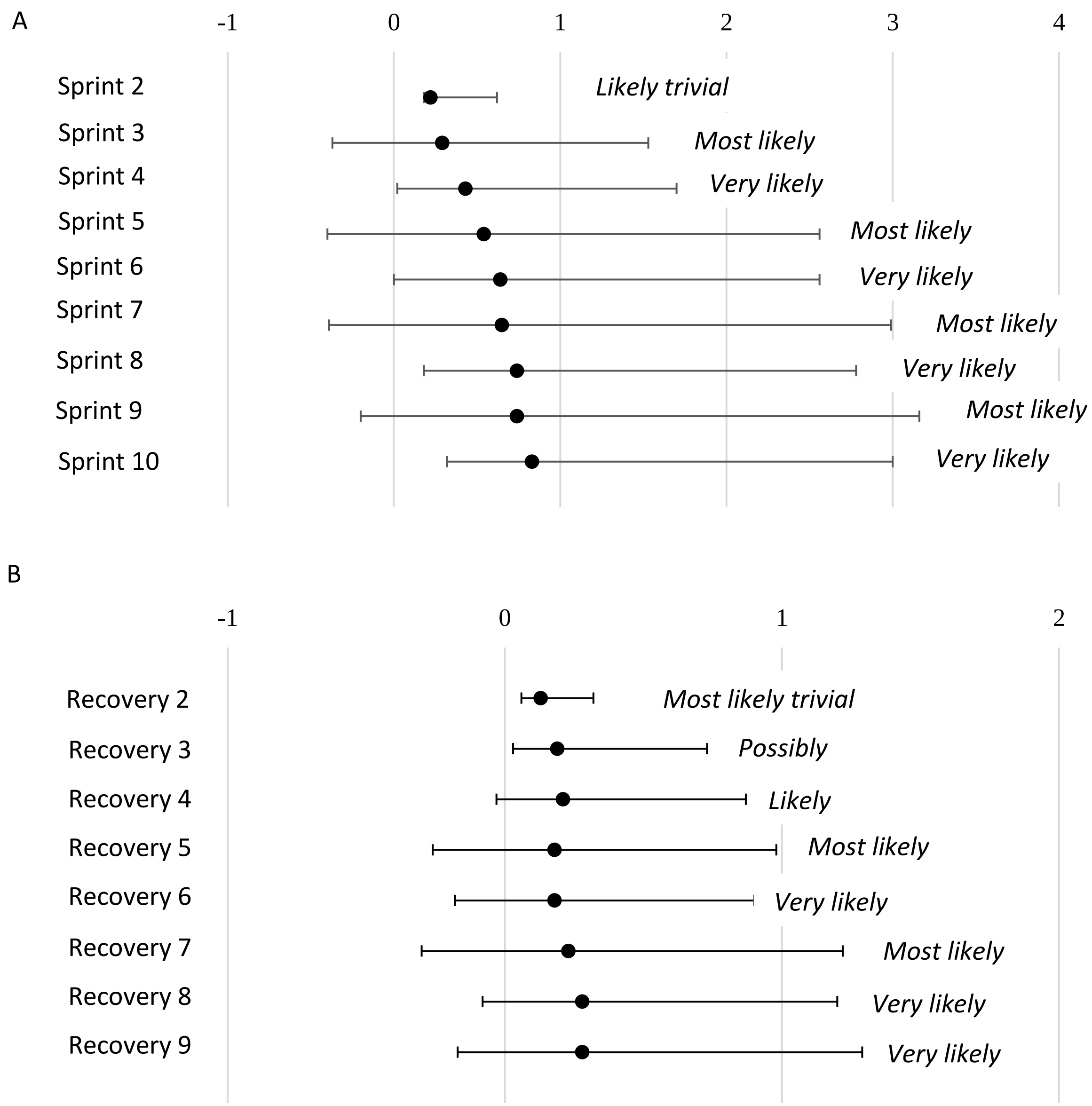


Figure 6: A (upper) and B (lower): Effect sizes with 90% confidence limits and magnitude of change when sprint one was compared to subsequent sprints (A) and recovery intermissions compared to intermission one (B) for pre-PHV players in the self-selected trial.

6.3.4 Within-group analysis post-PHV group

Physiological and performance data are displayed in Table 7, while average sprint times in the post PHV group during externally regulated and self-selected recovery trials are displayed in Figures 7A and B. Mean sprint duration was *likely* shorter in the externally regulated compared with the self-selected recovery trial (2.3%; ES = 0.44 ± 0.32; P = 0.03) whilst *small* differences were found between trials for fastest sprint time (1.3%; ES = 0.35 ± 0.34; P = 0.09). There were small differences in percentage sprint decrement (27.5%; ES = 0.34 ± 0.47; P = 0.41) between the externally regulated compared with the self-selected recovery trial. Mean recovery duration was *most likely* (46.4%; ES = 1.01 ± 0.49; P = 0.001 longer in the externally regulated compared with self-selected recovery trial. Mean HR was *likely* (2.4%; ES = 0.39 ± 0.21; P = 0.04) lower and peak HR was *very likely* (4.1%; ES = 0.71 ± 0.32; P = 0.01) lower in the externally regulated compared to self-selected recovery trial.

When comparing sprint times, there as a small difference between sprint two and the initial sprint (1.5%; ES 0.36 ± 0.32; P = 0.07). The magnitude of the increase in sprint time when compared to the initial sprint for all other intervals were, *likely* for sprints three (2.4%; ES 0.56 ± 0.35; P = 0.01), four (2.7%; ES 0.63 ± 0.42; P = 0.02), five (3.7%; ES 0.86 ± 0.58; P = 0.03), six (3.3%; ES 0.77 ± 0.57; P = 0.04), seven (3.1%; ES 0.72 ± 0.67; P = 0.08), nine (3.5%; ES 0.82 ± 0.73; P = 0.07) and ten (3.0%; ES 0.71 ± 0.82; P = 0.2) and *very likely* for sprint eight (4.1%; ES 0.95 ± 0.59; P = 0.02). For the externally regulated recovery trial there were small differences between sprints two (1.5%; ES 0.24 ± 0.16; P = 0.02), three (1.5%; ES 0.25 ± 0.23; P = 0.08), four (2.2%; ES 0.35 ± 0.21;P = 0.01), six (2.2% ES 0.36 ± 0.22; P = 0.14), eight (2.0%; ES 0.32 ± 0.31; P = 0.11) and ten (1.8%; ES 0.3 ± 0.25; P = 0.06). The differences for sprints seven (3.6%; ES 0.58 ± 0.31; P = 0.001) and nine (3.2%; ES 0.51 ± 0.3; P = 0.01) were *likely*.

There was a trivial difference between the second sprint intermission and the initial intermission (6.3%; ES 0.16 ± 0.43; P = 0.37). The difference in duration of between sprint recovery intervals when compared to the first intermission for all other comparisons was *very likely* for intermissions three (31.6%; ES 0.74 ± 0.41; P = 0.01), four (31.5%; ES 0.74 ± 0.43; P = 0.01) and eight (33.1% ES 0.77 ± 0.4; P = 0.001) and *most likely* for intermissions five (45.7; ES 1.02 ± 0.33; P = 0.001), six (36.2%; ES 0.84 ± 0.31; P = 0.001), seven (50.3%; ES 1.10 ± 0.34; P = 0.001) and nine (50.0%; ES 1.1 ± 0.36; P = 0.01).

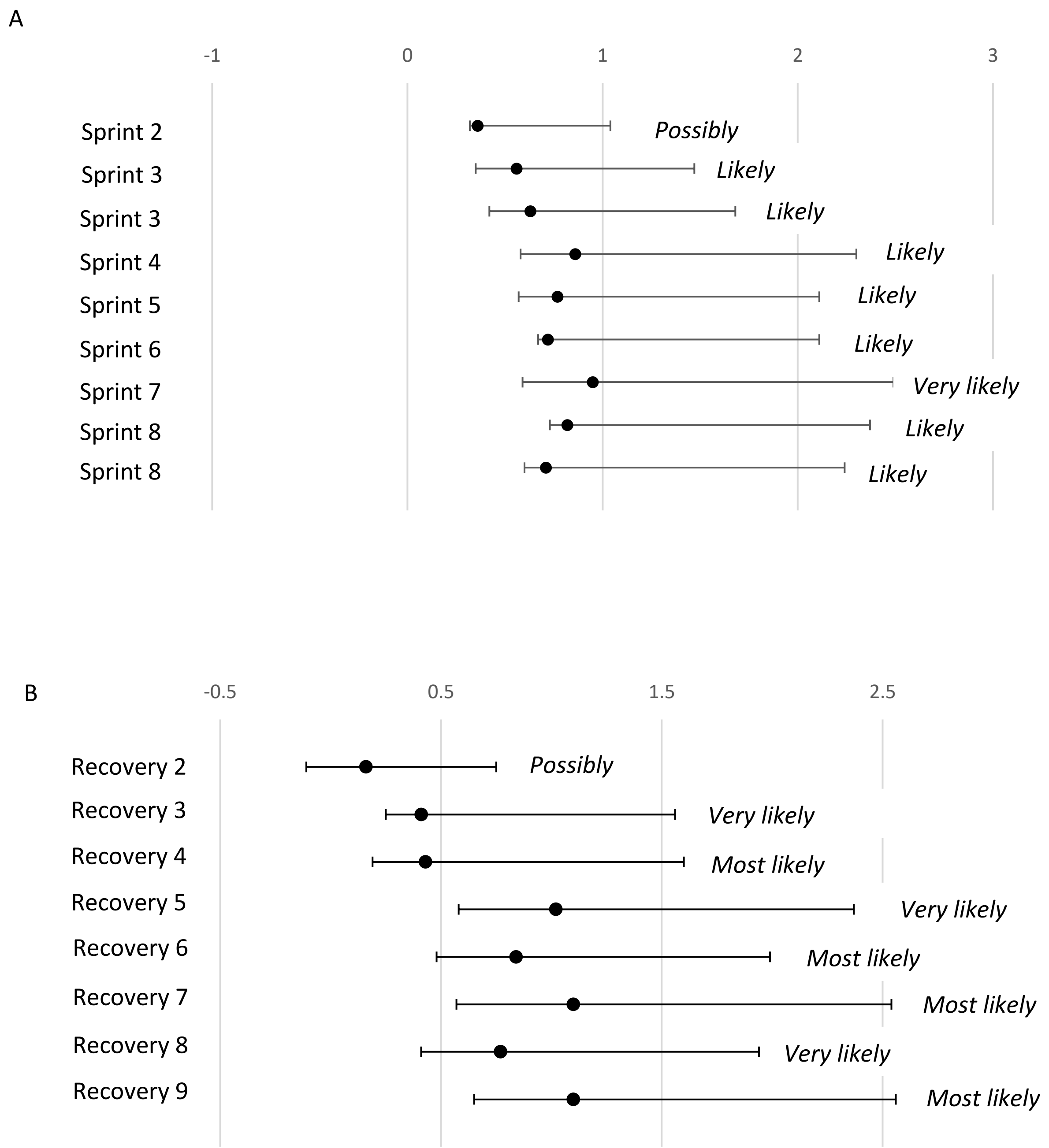
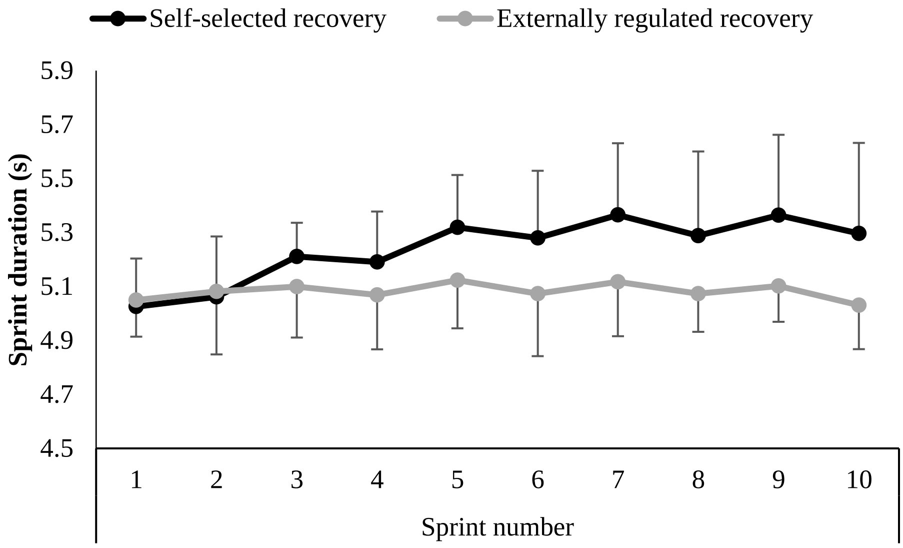


Figure 7: A (upper) and B (lower) Effect sizes with 90% confidence limits and magnitude of change when sprint one was compared to subsequent sprints (A) and recovery intermissions compared to intermission one (B) for pre-PHV players in the self-selected trial.

A



B

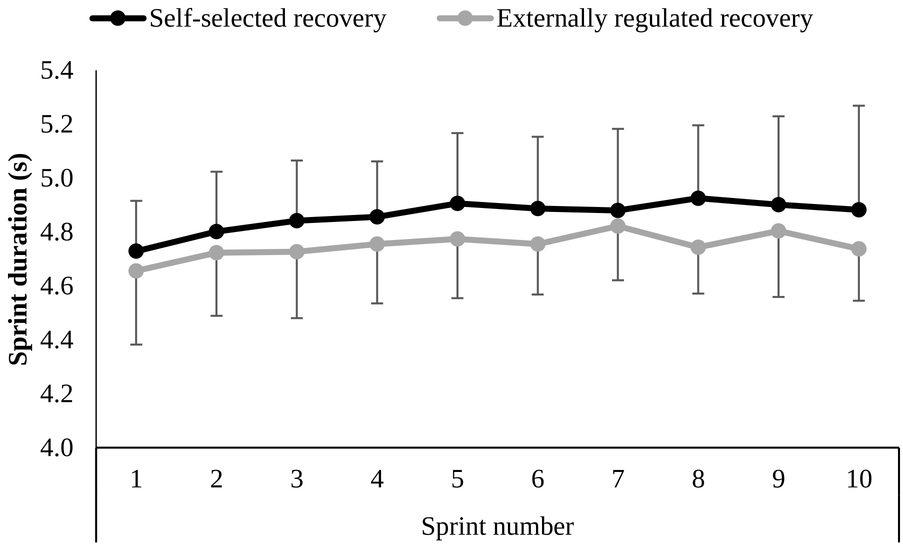


Figure 8: A (upper) and B (lower): Sprint durations during externally regulated and self-selected recovery trials for (A) pre-PHV players [n = 14] and (B) post-PHV players [n = 14].

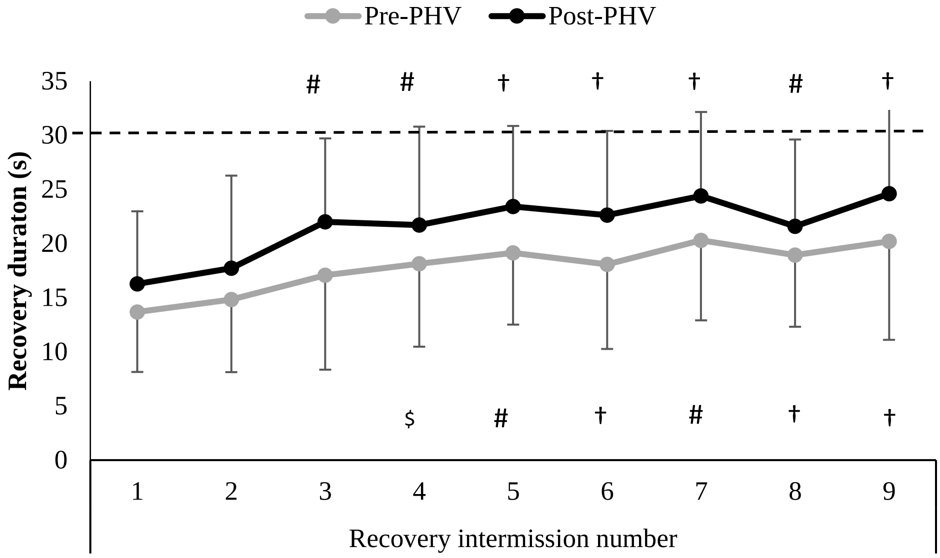


Figure 9: Between sprint recovery durations during repeated sprint trials with externally regulated recovery for the post-peak-height-velocity group (n=14) and pre-peak-height-velocity group (n=14). Values are mean ± SD. Differences in comparison with initial recovery interval indicated by $ = *likely*, # = *very likely*, † = *most likely*. Dashed line represents the duration of recovery in the externally regulated trial.

6.4 DISCUSSION

The results of this study show that irrespective of whether players are pre- or post-PHV, performance during repeated sprints separated by self-selected recovery periods is impaired when compared to sprints interspersed with externally regulated recovery. These data support those reported in Chapter 5 and collectively suggest that academy footballers when given autonomy over between sprint recovery duration lack the ability to maintain performance when the aim is to replicate running speed in the initial sprint. Differences in performance were, however, observed between maturation groups as a result of *likely* longer recovery time allocated by the post-PHV group. Percentage decrement was lower in the pre-PHV group in the externally regulated recovery trial yet higher by a *likely* magnitude when sprints were separated by self-selected recovery compared to the post-PHV group. These data suggest that pre-PHV players are less able to select appropriate recovery intermissions separating repeated sprints than those at a more advanced stage of biological maturation and that self-selected recoveries may negate the physiological advantage that has been reported elsewhere among pre-PHV populations to recover between successive routs of high intensity exercise (Armstrong et al., 2015; Ratel, Williams, et al., 2006). Given the complex interplay of factors that determine successful performance in academy footballers, including the necessary physical qualities combined with the knowledge of how and when to use them most effectively, these data are useful for the applied practitioner in the interpretation of fitness data as well as how best to programme and schedule training for players at different stages of biological maturation.

A *likely* lower percentage decrement was observed in the pre- compared to post-PHV group when externally regulated between sprint recovery intervals were used. The differences in fatigue susceptibility between children and adolescents have been well established (Bottaro et al., 2011) with children observed to fatigue less and recover faster than adolescents during high intensity exercise (Bottaro et al., 2011; Buchheit, Al Haddad, Mendez-Villanueva, Quod, & Bourdon, 2011; Ratel, Duche, et al., 2006). Proposed mechanisms for the reduced fatigue susceptibility in less mature individuals include physiological factors and an enhanced oxidative capacity (Kaczor et al., 2005), faster resynthesis of Phosphocreatine stores between successive bouts of fatiguing exercise (Ratel et al., 2008), differential motor unit recruitment and usage (Dotan et al., 2012; Metaxas et al., 2014), an attenuated slow component linked to fatigue resistance (Poole & Jones, 2012; Rossiter, 2011) and more efficient removal of metabolic by-products (Falk & Dotan, 2006) when compared to adults. The data reported here reaffirms previous research that has reported an attenuated fatigue response in less mature populations when engaged in high intensity exercise with pre-determined and externally regulated recovery. It would appear that involvement in organised and structured training comprising multiple bouts of short, yet high intensity activity characteristic of football practice in an academy setting does not alter responses to high intensity exercise influenced by maturation.

Despite an enhanced ability to resist fatigue when recovery was externally regulated in the pre-PHV group, percentage decrement increased in the self-selected recovery trial. Although performance was impaired in both groups when self-selected recovery periods were used, the detrimental effect was greater in the pre-PHV group. This was likely because of shorter recovery periods observed averaging 3.8 s less than in the post-PHV group. As such, whilst, physiologically, pre-PHV players are better able to resist fatigue during a repeated sprint task in which the work to rest ratios are pre-determined (Ratel, Duche, et al., 2006) they seem unable to assess the temporal cues necessary to allocate recovery effectively when given autonomy over this aspect of the exercise challenge resulting in greater percentage sprint decrement.

The ability to maintain performance during repeated sprinting requires complex cognition to interpret afferent feedback, monitor changes in running speed and allocate recovery duration appropriately. During each recovery intermission, players must, in an anticipatory manner, consider their perception of exertion in light of the perceived demands associated with the remaining sprints. It should be remembered that in the present study, players had explicit knowledge of how many sprints and over what distances were included within the task; during match play such knowledge is not provided *a priori*. The self-regulation of recovery requires proactive, goal driven processes and reactive, stimulus driven processes which are influenced by previous experience, temporal cues and logical reasoning (Brick, MacIntyre, & Campbell, 2016). The latter, logical reasoning, would suggest that toward the start of a task players would allow more recovery to protect against premature fatigue, something that is apparent in adults during high intensity running interspersed by self-selected recovery periods (McEwan et al., 2018). In the present study, however, this was not the case as players allocated less recovery at the start of the repeated sprint task, extending the length of intermissions as the number of repetitions completed increased (Figures 7 and 8). Indeed, *most likely* decrements in sprint speed among the pre-PHV group were observed during the third repetition, however they did not increase recovery time to the same magnitude until after sprint six (recovery intermission 5: Figure 7A and b). Such an approach may suggest a less well developed cognitive ability and/or intellectual functioning, both of which are influential in the ability to apportion recovery intervals within the constraints of high intensity exercise tasks (Micklewright et al., 2012). It has been reported that children in the concrete operational stage of cognitive development who were of a similar age to the pre-PHV group in this study were less able to regulate intensity during exercise challenges that required the interpretation of temporal rather than spatial cues (Chinnasamy et al., 2013). The authors concluded that children might struggle to interpret the relationship between distance, space and time until the formal intelligence period of cognitive development that occurs between 14 and 18 years of age (Chinnasamy et al., 2013; Piaget, 1954). The assertion that adolescent players may struggle to interpret the relationship between time, space and distance would appear to corroborate data reported in Chapter 4 where players aged ~14 years were unable to discriminate between the demands of repeated sprinting and high speed running performed in the field and over specific distances. Further research is required to understand the effect of cognitive development on the ability of academy football players to pace their effort during tasks that require the interpretation of temporal and spatial cues and whether this may still inhibit performance beyond the age range reported for the development of formal intelligence (Piaget, 1954).

The etiology of fatigue during repeated sprints has been studied extensively with decrements in performance linked to energy supply and the accumulation of metabolic by-products. Specifically, degradation of Phosphocreatine and the accumulation of H+ ions and inorganic phosphate reduce the rate of adenosine triphosphate (ATP) resynthesis and negatively influence the excitation-coupling process, thereby contributing toward impairments in the force generating capacity of the muscle (Bogdanis, Nevill, Boobis, & Lakomy, 1996; Girard, Mendez-Villanueva, & Bishop, 2011; Goodall et al., 2015). Given that the resynthesis of ADP and removal of metabolic by-products are time dependent processes, it could be suggested that shorter recovery periods between sprints could lead to incomplete recovery of these intramuscular processes. Although markers of intramuscular recovery were not reported, in young footballers aged 16 years, performance denoted by the percentage sprint decrement was negatively affected when recovery time was reduced, albeit in a uniform and externally regulated manner (Padulo et al., 2015). In the present study and whilst acknowledging the faster recovery rates of Phosphocreatine (Taylor et al., 1997) and clearance of H+ ions (Ratel, Duche, et al., 2006) in children shorter recovery periods allocated by the pre and post-PHV groups, 17.8 and 21.6 s may have been insufficient for the restoration of intramuscular homeostasis and explain the decrements in performance when compared to externally regulated and longer recovery periods.

6.5. CONCLUSION

Self-selected recovery intervals during repeated sprinting have a detrimental effect on performance when compared to externally regulated recovery in pre- and post-PHV footballers. As in Chapter 5, players were found to underestimate the amount of recovery time needed between successive sprints necessary to maintain performance in line with the stated aim of the task. This negative effect was more pronounced in the pre-PHV compared to post-PHV players despite an enhanced ability to resist fatigue when recovery was externally regulated in the former compared to the latter. The extent to which this inability to interpret temporal cues in the allocation of appropriate recovery intermissions in pre-PHV players is as a result of less developed cognitive abilities remains to be elucidated.

6.6 PRACTICAL APPLICATIONS

Despite performance decrements in the self-selected recovery trial this method of prescribing repeated sprint training should not be discounted given the data reported here and in Chapter 5 relating to internal training load. A meta-analysis has highlighted that variables such as recovery duration can be manipulated in order to achieve different training outcomes, be that increasing internal load or enabling athletes to maintain specific running speeds across multiple repetitions (Taylor et al., 2015). When a greater contribution from the aerobic energy systems is sought, reducing the recovery time interspersing intervals can increase physiological stress and provide a more potent stimulus for adaptation through elevated heart rate and greater time spent in specific high intensity training zones. In the present study, self-selected recoveries resulted in higher peak and mean HR responses in both groups, a similar finding to chapter 5, and when viewed collectively would support the use of this approach where the aim of training is to elicit greater physiological disturbances. Conversely, if the aim is to preserve running speed over multiple repetitions, as is the case for speed endurance training, then self-selected recovery is not advised in academy footballers. From a practical and logistical perspective, practitioners should consider the role that peer influence may play in the selection of recovery intervals if players are training together. Practical solutions to this problem include staggering the start time for each player so that recovery intervals do not coincide, or, starting players at opposite ends of the 'sprint track' so they are not in close proximity of each other during the recovery intermissions. Furthermore, practitioners may exercise caution in the interpretation of fitness results from repeated sprint tests which use externally regulated work to rest ratios amongst players at differing levels of biological maturation.

CHAPTER 7: Movement characteristics and physiological responses associated with externally regulated and self-paced intermittent running interspersed with self-selected recovery during an incremental, intermittent high-speed running protocol to volitional exhaustion in academy football players.

7.1 INTRODUCTION

Previous chapters have identified that when academy footballers self-select recovery between repeated sprints there are decrements in running performance compared to when between sprint rest periods are externally regulated (Chapters 5 and 6). Performance decrements, however, are mitigated by maturation with more mature players able to attenuate increases in percentage decrement when recovery is self-selected compared to their less mature peers (Chapter 6). Furthermore, in Chapter 5 two individuals performed better when repeated sprints were interspersed with self-selected recovery despite allocating less total recovery time than when scheduled in a pre-determined and uniform manner. In Chapter 4 and despite differences in the speed at which repeated sprints and high speed runs were prescribed at, resultant movement characteristics when performed in the field were similar. Collectively these data raise questions regarding the ability of academy footballers to replicate performance in externally regulated protocols when required to self-select between effort recoveries and/or self-pace running speed. Given the prevalence of the YoYo assessment in football (Bangsbo et al., 2008; Bradley et al., 2012; Bradley et al., 2011; Krustrup et al., 2003) as a tool for assessing high speed running ability, an investigation into how performance might differ under self-paced conditions is warranted. Indeed, assessment protocols that are self-paced may give a better indication of the ability of the player to use their physical prowess in the most effective and timely manner. This has been described as understanding the skill of the driver [self-paced assessment] as well as the size of the engine [externally regulated assessment] (Gibson & McCunn, 2018). This is especially pertinent given the data reported in Chapter 6, which showed that the ability to maintain performance across multiple bouts of high intensity exercise was compromised under self-selected versus externally regulated conditions.

The YoYo intermittent recovery test level 1 (YYIRT1) is widey used amongst academy footballers and involves shuttle running at increasing speeds with each 40 m shuttle interspersed by 10 s of active recovery (Krustrup et al., 2003). Perfrmance within the YYIRT has been used to identify more and less successful players (Waldron & Murphy, 2013), to assess the effectiveness of training programmes (Taylor et al., 2015) and to prescribe running velocities for high speed running conditioning sessions as demonstrated in Chapter 4. The test is also, in applied settings, used to measure a maximal heart rate for use in the quantification of internal load in subsequent trainng sessions. During the assessment, running speeds and the recovery intermissions that separate each 40 m shuttle are established *a priori*. Although this protocol has been shown to be valid and reliable (Krustrup et al., 2003) the test removes autonomy from those performing it; running speeds and recover durations are controlled by an audio cue. Previous chapters have shown that academy footballers are unable to differentiate between the running demands of repeated sprints and high speed runs when performed in series within a field setting (Chapter 4) and during repeated sprinting suffer detrimental changes in perfrmance when allowed to self-select between effort recovery periods (Chapters 5 and 6). As such, investigating how performance and the physiological responses that ensue would be affected if the YYIRT1 were performed with self-selected running speeds and recovery intermissions seems warranted. A similar approach using laboratory protcols for the determination of maximal aerobic capacity has been examined previously with mixed results (Chidnok et al., 2013; Harley et al., 2010; Mauger & Sculthorpe, 2012). When compared to an externally regulated, incremental protocol with pre-defined running speeds, maximal aerobic capacity has been shown to increase (Mauger & Sculthorpe, 2012) and remain unchanged (Chidnok et al., 2013) when participants regulated their running speed anchored to a specifc RPE value. However, these studies were conducted using continuous exercise, a training and testing modality that does not reflect the intermittent nature of football match play and training (Buchheit, Mendez-villanueva, et al., 2010b; Mendez-Villanueva et al., 2013). To date no studies have investigated a self-paced approach to intermittent exercise when participants regulate running speed and the recovery periods that separate bouts of high intensity exercise.

In self-paced assessments performed to maximal volitional exhaustion, running speed was controlled using ‘clamps’ established through RPE values linked to specific intensity domains of exercise (Hartshorn & Lamb, 2004; Marriott & Lamb, 1996). Such an approach requires participants to be able to regulate exercise intensity using afferent feedback to approximate a specific exertion level on the Borg scale. The ability of young athletes to do this remains unclear. Australian Rules Footballers (19.0 ± 1.8 years) displayed poor reliability in their RPE following externally regulated periods of sub-maximal exercise (Scott et al., 2013). When young, multisport athletes aged 16.4 ± 0.9 years were asked to replicate percentages of their maximal sprint speed under self-regulated conditions their accuracy in doing so improved at higher speeds (Uthoff, Oliver, Cronin, Winwood, & Harrison, 2018). The results presented to date are ambiguous regarding the ability of young athletic populations to self-regulate exercise at specific RPE values, and to date none have included the requirement to apportion recovery intermissions separating periods of intermittent high intensity running.

The aim of this chapter was to compare the phsyiological responses, recovery scheduling and movement characteristics during an externally regulated and self-regulated version of the YYIRT1 in academy footballers. The research hypothesis for this study states that performance in the externally regulated version of the YYIRT1 compared to a self-paced version would be different when considering total distance, fidelity of runing speeds to those denoted by the audio signal and allocation of between shuttle recovery duration. The research hypothesis also stated there would be differences in the physiological responses associated with each version.

7.2 METHODS

7.2.1 Participants

Seven outfield players from the same professional football club volunteered to take part in the study (18.3 ± 1.2 years, 178.5 ± 7.7 cm and 71.7 ± 10.3 kg). Post-hoc sample size calculation identified 22 participants were required for the identification of a *moderate* effect based on running speed in the self-selected recovery trial. All players were engaged in full time training and registered under professional contracts at the same academy. Data were collected at the midway point in the season immediately before a mid-season break in training and competition of 10 days. Before the study, participants had the procedures explained to them and provided informed consent to participate. All players were approved to participate in maximal and strenuous exercise by medical and sport science staff. The study received institutional ethics approval from the University of Chester's Faculty of Medicine, Dentistry and Life Sciences Ethics Committee and complied with the Declaration of Helsinki.

7.2.2 Design

The study comprised three trials that were performed consecutively. In the first trial players performed the YYIRT1 during which RPE were collected at the end of each stage during the 10 s intermission separating the final shuttle in the previous stage and first shuttle in the next stage. In the second and third trials players were informed at the start and midway point of each stage of their RPE from the first trial with an instruction to self-regulate their running speed and recovery duration to maintain an equivalent RPE. They completed the same number of shuttles within each stage as trial one. All trials were conducted at the same time of day, between 09:30 and 10:30 before normal squad training. Trials were conducted on an outdoor synthetic pitch (mean temperature 7 ± 3°C; humidity 82 ± 6%; pressure 1008 ± 52 mb, wind speed 7.2 ± 3.6 $km \cdot h^{-1}$) with players instructed to wear their normal football training attire and boots. Data were collected in the month of December prior to a Christmas intermission in training of two weeks. Assessments were conducted individually to eliminate any effect of peer influence and participants wore portable micro-technology devices and heart rate monitors throughout each assessment for the quantification of movement characteristics and internal training load. Due to scheduling changes and players being selected to train with the first team, only four players conducted the third trial and as such this data is presented to illustrate individual differences using a 'case study' approach.

7.2.3 YYIRT1

For details of how the YYIRT1 was performed including the collection of movement characteristic data, please refer to the General Methods chapter, section 3.3.

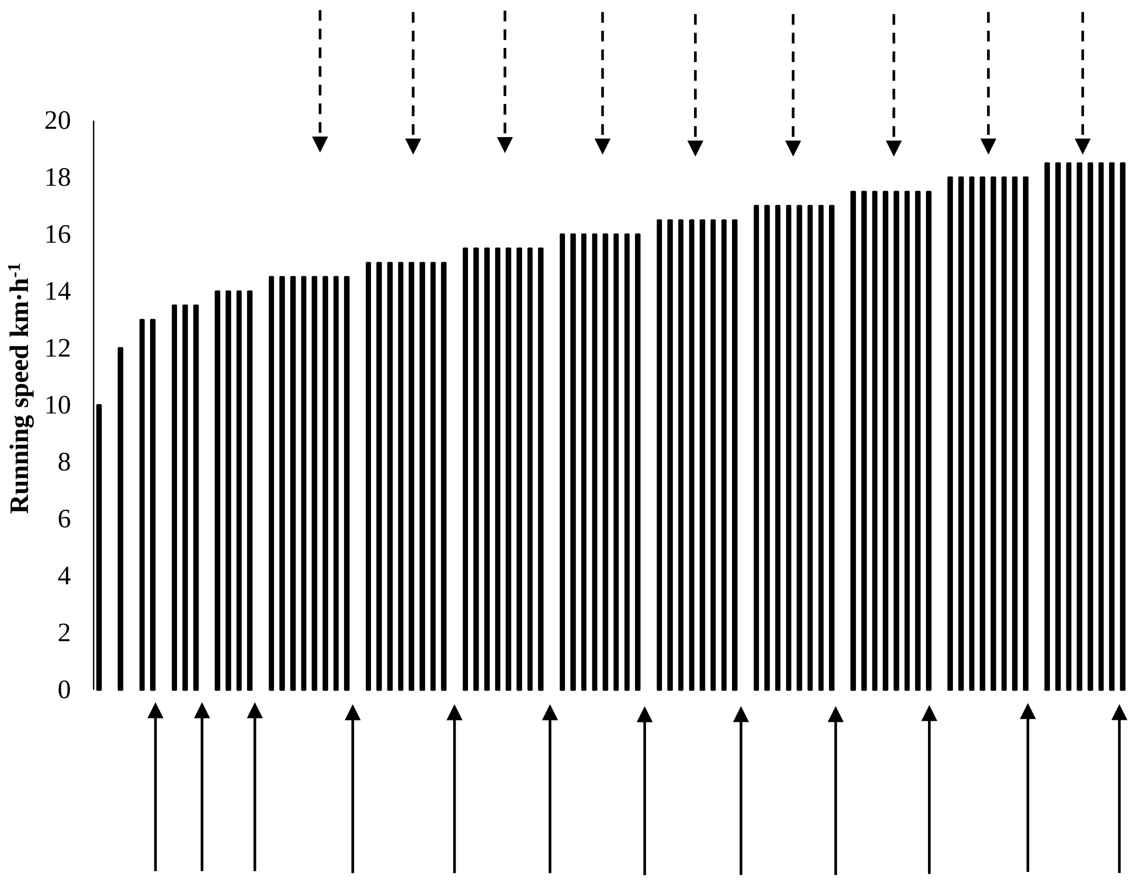


Figure 10: Schematic showing levels and individual shuttles therein. Solid black arrows denote the collection and verbal reporting of RPE in the externally regulated and self-paced trials, respectively. Dashed black arrows denote the verbal communication of RPE values in the estimation trial, half way through each level.

7.2.4 Self-paced YYIRT

After a self-selected 5 min warm up, that included jogging, dynamic stretching and striding, players ran the first two shuttles of the protocol which corresponded to Level 5 and 9 of the YYIRT1 to habituate them with the method the investigator used to communicate RPE. After the warm up, players were allowed to stretch until they verbally indicated they were ready to start the test. Players were instructed to select running speeds and recovery intermissions that allowed them to complete each stage and its corresponding number of shuttles at the RPE recorded during the externally regulated trial. At the start of each new stage and during the recovery intermission separating it from the last shuttle in the previous stage, the new RPE was communicated verbally. A scale was also held up for the participant with the corresponding RPE physically indicated by the investigator (Figure 10). Participants were verbally reminded of the RPE they should be working to half way through each stage during the recovery intermission that followed the mid point shuttle. No other information was provided to the players during the assessment. Players were instructed to continue exercising until achieved in the externally regulated trial. If they were able to continue exercising beyond the point of volitional exhaustion in the externally regulated trial players were instructed to maintain the final RPE for as long as possible. For details relating to the collection of movement characteristic and heart rate data were readers should refer to the General Methods sections, 3.5 and 3.7 respectively.

7.2.5 Intensity bands

Previous research has examined the reproducibility of external and internal measures of load at specific RPE values during continuous exercise (Scott et al., 2013). As this is not a practise commonly used with academy football players, physiological responses, recovery distribution and movement characteristics in five intensity bands characterised by their ‘anchors’ in the original Borg scale were used. These were *light* (6-11), *somewhat hard* (12-13), *hard* (14-15), *heavy* (16-18) and *maximal* (19-20).

7.2.6 Statistical analysis

Effect sizes (ES) ± 90% confidence limits, relative change (in percentages) expressed as the transformed (natural logarithm) ± 90% confidence limits, and magnitude based inferences were calculated for all outcome measures. Effect sizes were defined as: *trivial* = 0.2; *small* = 0.21–0.6; *moderate* = 0.61–1.2; *large* = 1.21–1.99; *very large* > 2.0 (Hopkins et al., 2009). Threshold probabilities for a substantial effect based on the 90% confidence limits were <0.5% most unlikely, 0.5-5% very unlikely, 5-25% unlikely, 25-75% possibly, 75-95% likely, 95-99.5% very likely, and >99.5% most likely (Hopkins et al., 2009). Only probabilities greater than 75% were reported, effect sizes were reported for differences that did not achieve this threshold. Thresholds for the magnitude of the observed change for each variable were determined as the between participant SD x 0.2, 0.6 and 1.2 for a small, moderate and large effect, respectively. Effects with confidence limits across a likely small positive or negative change were classified as *unclear* (Hopkins et al., 2009). For those wishing to interpret the analysis using a more traditional approach, p-values based on appropriate null hypothesis tests are also included using SPSS (SPSS Inc, Chicago, IL, USA).

7.3 RESULTS

7.3.1 Whole assessment analysis

There were trivial differences (0.6%; ES 0.02 ± 0.04; P = 0.36) in distance covered between the externally regulated (2554 ± 499 m) and self-paced (2537 ± 480 m) versions of the YYIRT1; however, the self-paced version was *likely* (-7.7%; ES 0.56 ± 0.66; P = 0.16) shorter in total duration (1296 ± 152 s and 1195 ± 13 s, respectively) as a result of less total time taken for recovery between shuttles. Small differences in total recovery time were reported (13.3%; ES 0.58 ± 0.81; P = 0.16) in the externally regulated (634 ± 125 s) compared to self-paced (552 ± 132 s) version of the YYIRT1, with *trivial* (P = 0.27) differences in the average recovery duration (10 ± 0 s cf. 9.2 ± 1.9 s) in the externally regulated and self-paced version of the YYIRT1, respectively. The distribution of average between shuttle recovery periods are illustrated in Figure 11. Differences in maximal heart rate were trivial (0.4%; ES 0.09 ± 0.71; P = 0.8) between the externally regulated (190 ± 7.8 $b \cdot min^{-1}$) and self-paced (189 ± 7.6 $b \cdot min^{-1}$) versions of the YYIRT1. Peak running speed achieved in the self-paced (21.8 ± 1.4 $km \cdot h^{-1}$) was *likely* (4.1%: ES 0.63 ± 0.43; P = 0.03) higher than in the externally regulated YYIRT1 (20.9 ± 1.1 $km \cdot h^{-1}$). Conversely, the average running speed in the self-paced (13.5 ± 1.2 $km \cdot h^{-1}$) was *likely* (6.5%; ES 0.67 ± 0.51; P = 0.05) slower than the externally regulated (12.7 ± 1.6 $km \cdot h^{-1}$) YYIRT1.

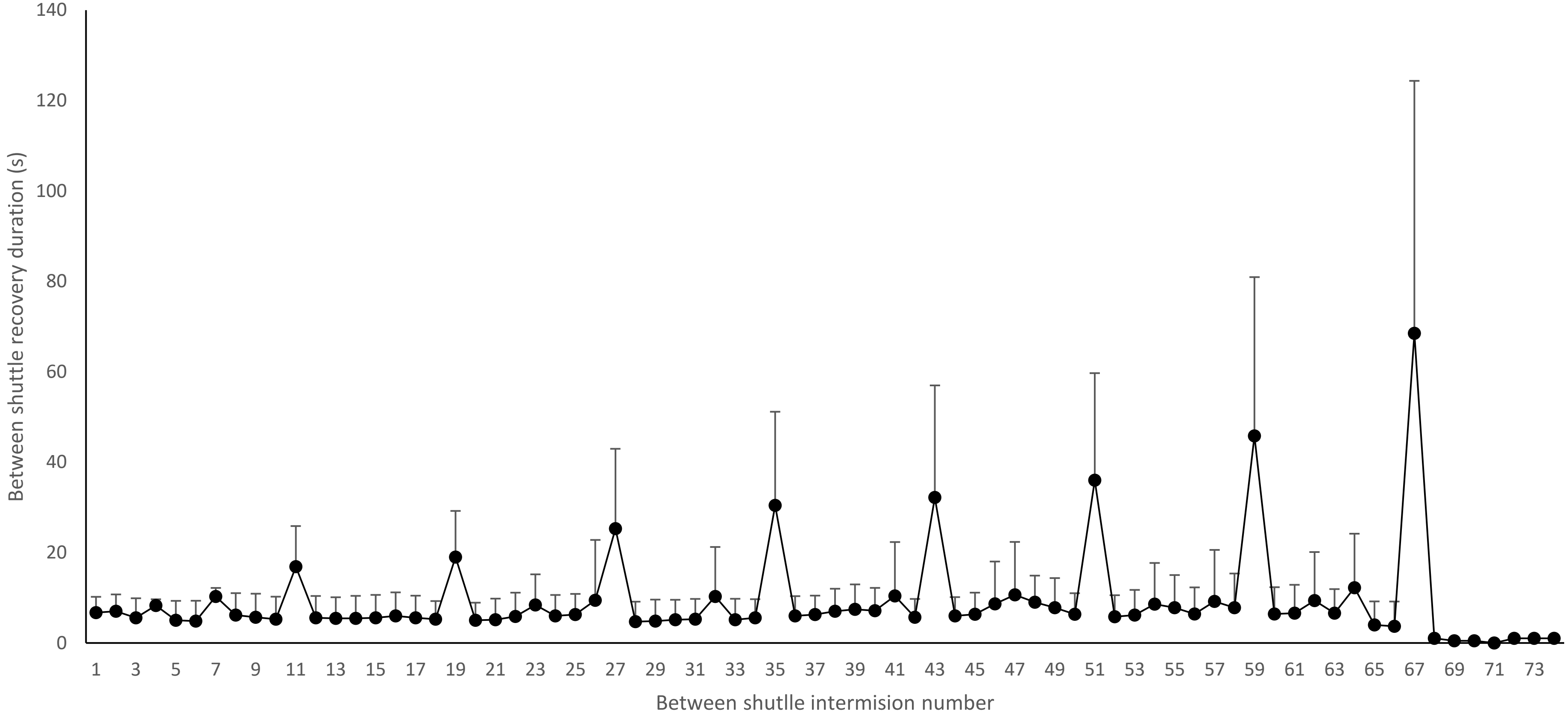


Figure 11: Between shuttle recovery duration for each player during the self-paced version of the YYIRT1

7.3.2 Intensity band comparison: RPE 6-11 [light]

Individual data for HR (% maximum) and average running velocity for externally regulated and self-paced versions of the YYIRT1 along with average between shuttle recovery duration in the self-paced versions of the YYIRT1 are presented in Figure 12 A-C. Peak running speed (7%; ES 0.74 ± 0.85; P = 0.03) and average running speed (7.5%; ES 0.65 ± 0.92; P = 0.05) were *likely* faster in the externally regulated compared to self-paced version of the YYIRT1 whilst differences in PlayerLoad^{TM} were trivial (1.3%; ES 0.1 ± 0.69; P = 0.24). Small differences in total recovery duration (30.3%; ES 0.4 ± 0.54; P = 0.27) were observed in the self-paced compared to externally regulated version of the YYIRT1, with the average between shuttle interval in the self-paced version being 9.0 s and ranging from a minimum of 0.0 to a maximum of 31.0 s. The average heart rate (%maximum) was *very likely* higher in the self-paced compared to externally regulated version of the YYIRT1 (16.3%; ES 1.51 ± 0.95; P = 0.03).

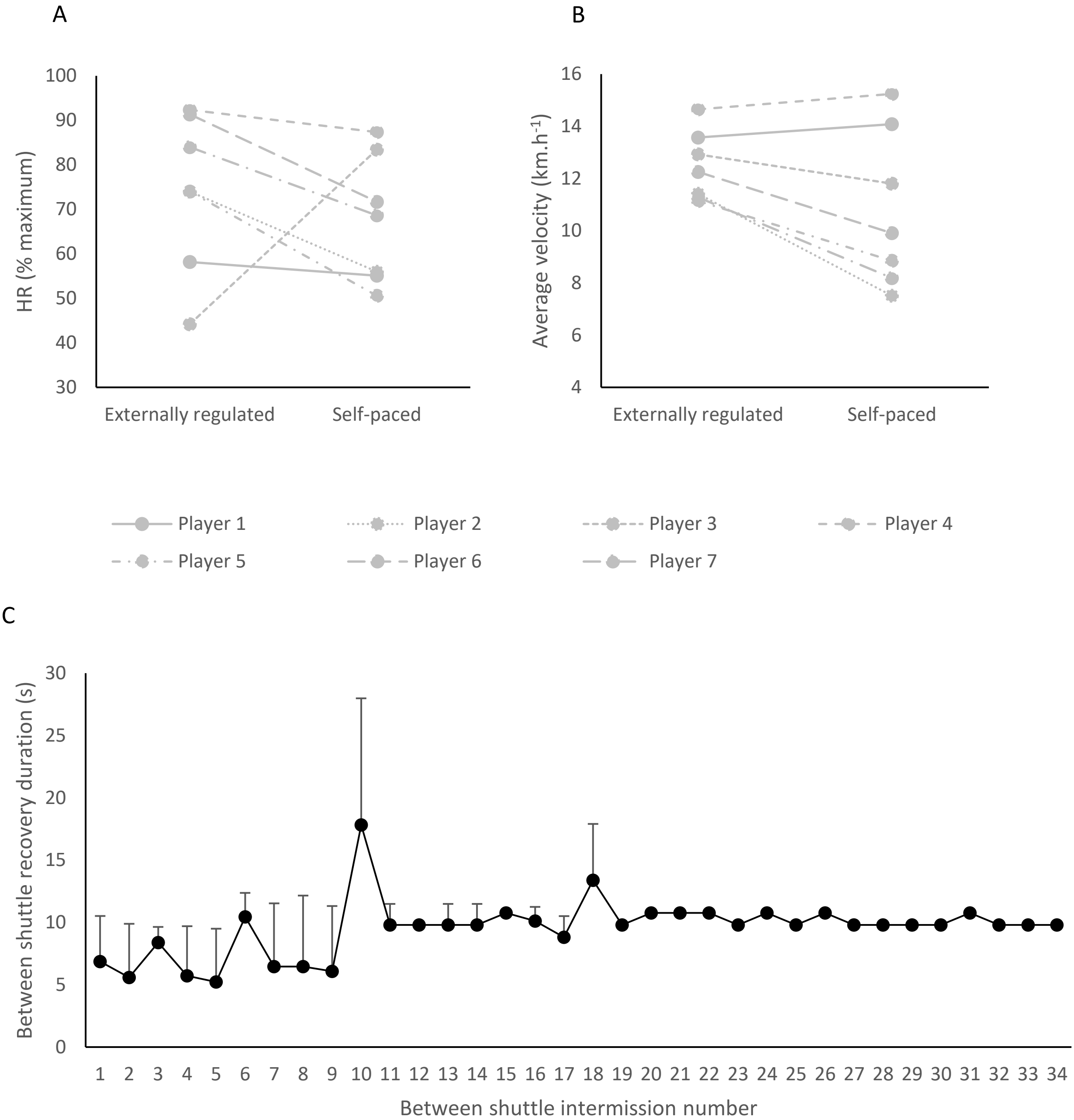
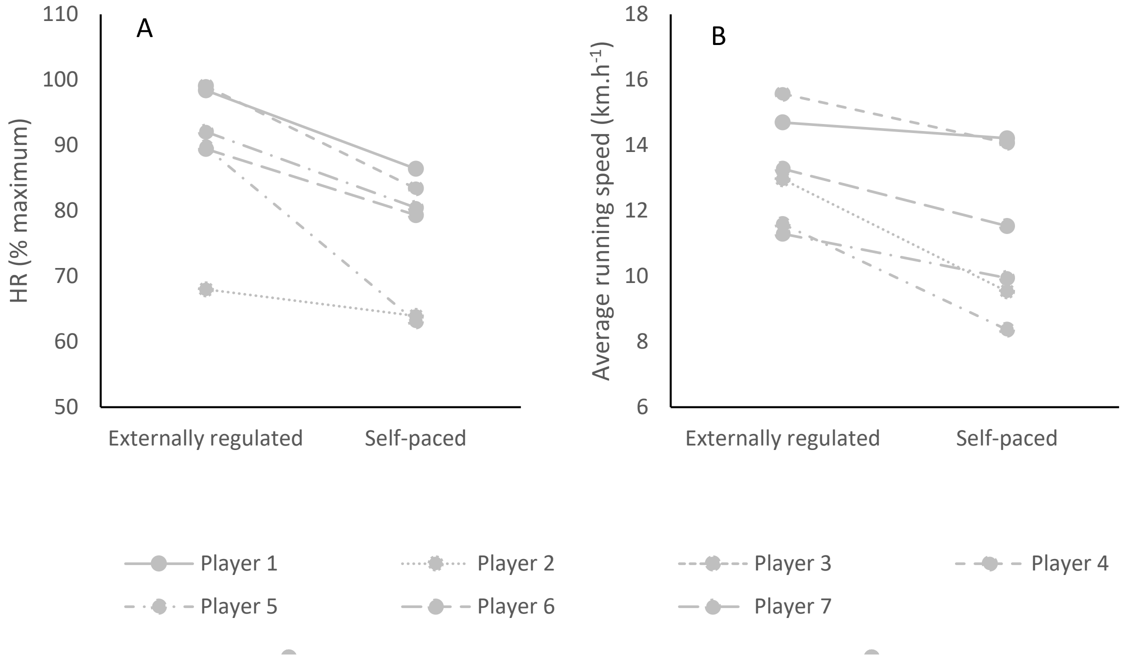


Figure 12: HR (% maximum) (A), average velocity (km·h^{-1}) (B) for each player and average between shuttle recovery periods for all players (C) in self-paced version of the YYIRT1 at RPE values in the light intensity band (6-11).

7.3.3 Intensity band comparison: RPE 12-13 [somewhat hard]

Individual data for HR (% maximum) and average running velocity for externally regulated and self-paced versions of the YYIRT1 along with average between shuttle recovery duration in the self-paced versions of the YYIRT1 are presented in Figure 13 A-C. Peak running speed (11.6%; ES 1.35 ± 0.56; $P < 0.01$) and average running speed (13.8%; ES 1.24 ± 0.27; $P < 0.01$) were *most likely* faster in the externally regulated compared to self-paced versions of the YYIRT1 protocol. PlayerLoad™ (9.4%; ES 0.58 ± 0.34; $P = 0.03$) was *likely* higher in the externally regulated protocol whilst heart rate (% maximum) was *most likely* higher in the self-paced version of the YYIRT1 protocol (15.7%; ES 2.64 ± 0.45; $P < 0.001$). Total recovery was *likely* (47.1%; ES 0.97 ± 0.76; $P = 0.07$) lower in the self-paced compared to externally regulated version of the YYIRT1. In the self-paced version the average between shuttle recovery duration was 7.0 with a minimum of 0.0 and maximum of 23.0 s.



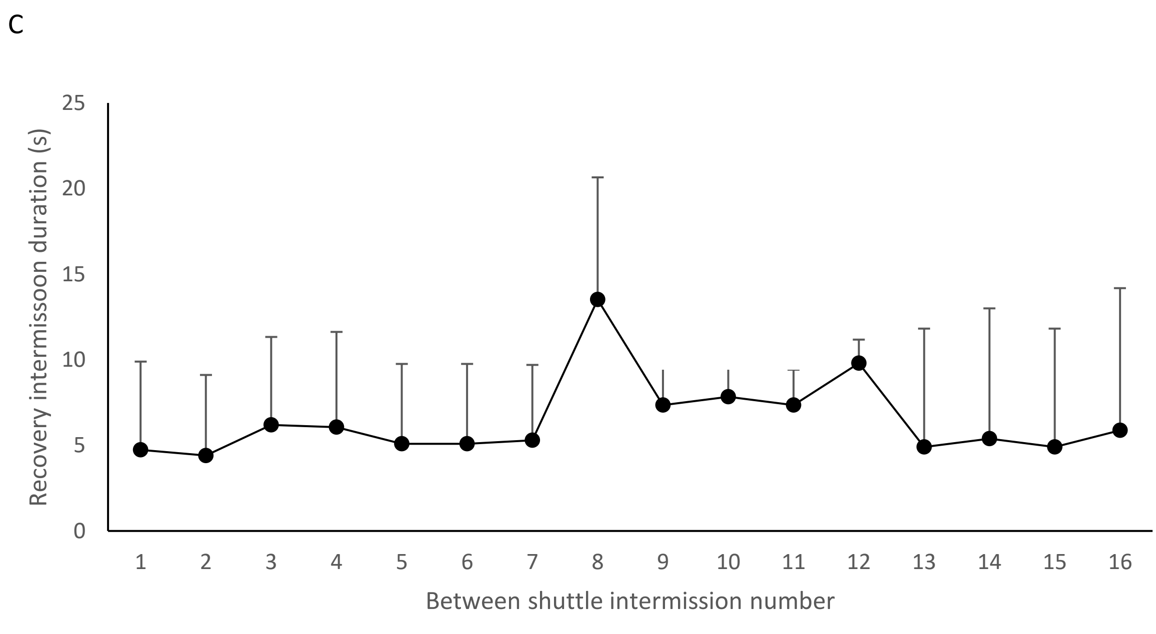


Figure 13: HR (% maximum) (A), average velocity (km·h^{-1}) (B) for each player and average between shuttle recovery periods for all players (C) in self-paced version of the YYIRT1 in the somewhat hard intensity band (12-13).

7.3.4 Intensity band comparison: RPE 14-15 [hard]

Individual data for HR (% maximum) and average running velocity for externally regulated and self-paced versions of the YYIRT1 along with average between shuttle recovery duration in the self-paced versions of the YYIRT1 are presented in Figure 14 A-C. Peak running speed (15.6%; ES 3.44 ± 0.4; P = 0.02) and average running speed (15.8%; ES 2.01 ± 0.3; P = 0.06) were *most likely* faster in the externally regulated compared to self-paced version of the YYIRT1 protocol. Small differences in PlayerLoad™ (4.5%; ES 0.33 ± 0.18; P = 0.9) and total recovery duration (22.6%; ES 0.52 ± 0.8; P = 0.2) were noted in the self-paced compared to externally regulated version of the YYIRT1 protocol. Average between shuttle recovery duration in the self-paced version of the YYIRT1 was 8.0 s with a minimum of 0.0 and maximum of 59.0 s. Heart rate (% maximum) was *most likely* higher in the externally regulated compared to self-paced protocols versions of the YYIRT1 protocol (13.3%; ES -1.69 ± 0.25; P = 0.46).

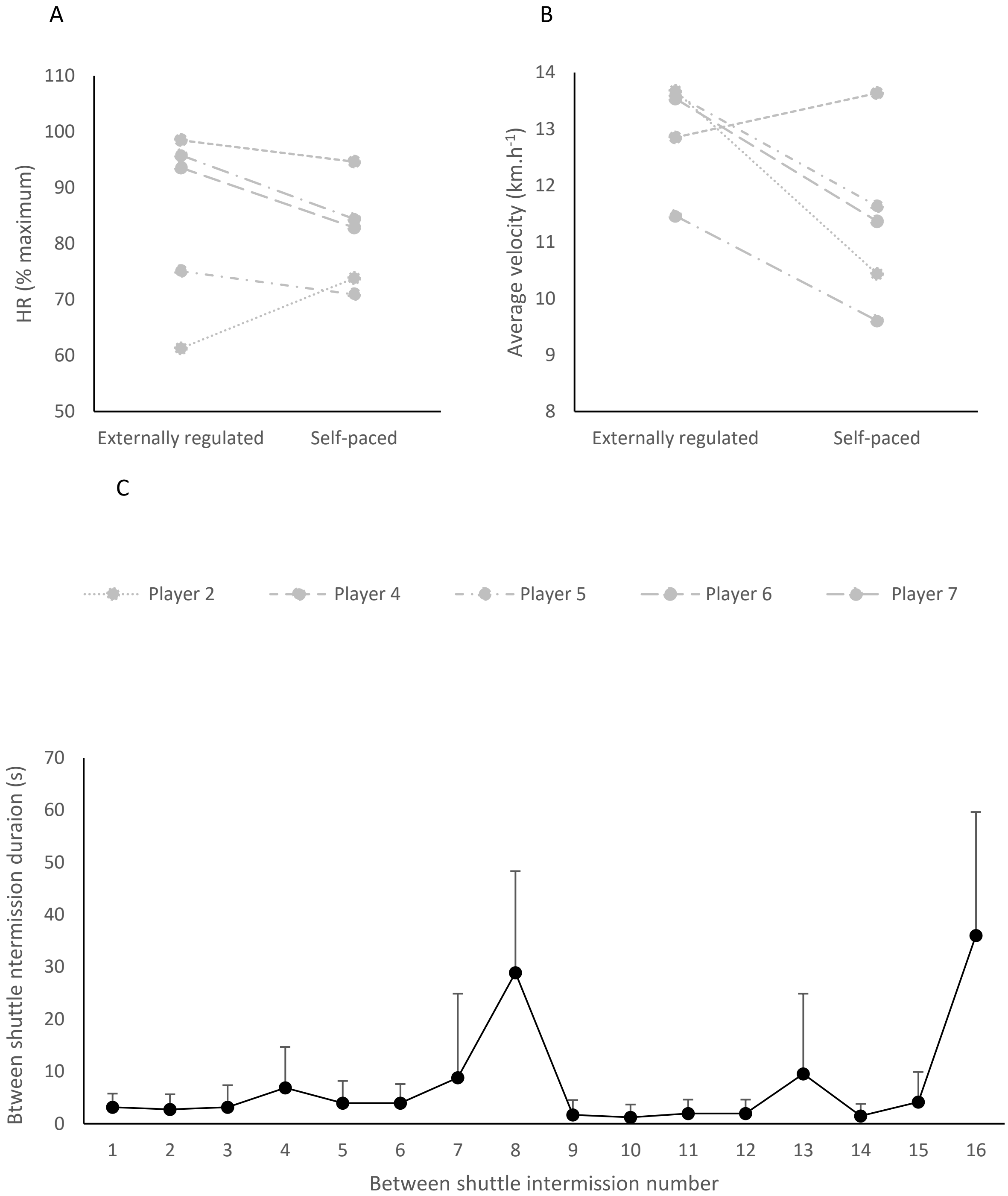


Figure 14: HR (% maximum) (A), average velocity (km·h^{-1}) (B) for each player and average between shuttle recovery periods for all players (C) in the self-paced version of the YYIRT1 at RPE values in the somewhat hard intensity band (14-15).

7.3.5 Intensity band comparison: RPE 16-18 [heavy]

Individual data for HR (% maximum) and average running velocity for externally regulated and self-paced versions of the YYIRT1 along with average between shuttle recovery duration in the self-paced versions of the YYIRT1 are presented in Figure 15 A-C. Peak running speed (5.4%; ES 0.93 ± 0.3; P = 0.22) was *most likely* faster whilst average running speed (4.9%; ES 0.45 ± 0.2; P = 0.31) was *likely* faster in the externally regulated compared to self-paced version of the YYIRT1 protocol. There were trivial differences in PlayerLoad^{TM} between versions of the YYITR1 (2.4%; ES 0.17 ± 0.15; P = 0.58). The average heart rate (% maximum) was *most likely* higher in the externally regulated compared to self-paced version of the YYIRT1 protocol (8.9%; ES 1.66 ± 0.3; P = 0.03). Differences in total recovery duration within the heavy intensity band were trivial whilst the average between shuttle recovery duration was 10 s with a minimum of 0.0 and a maximum of 78.0 s.

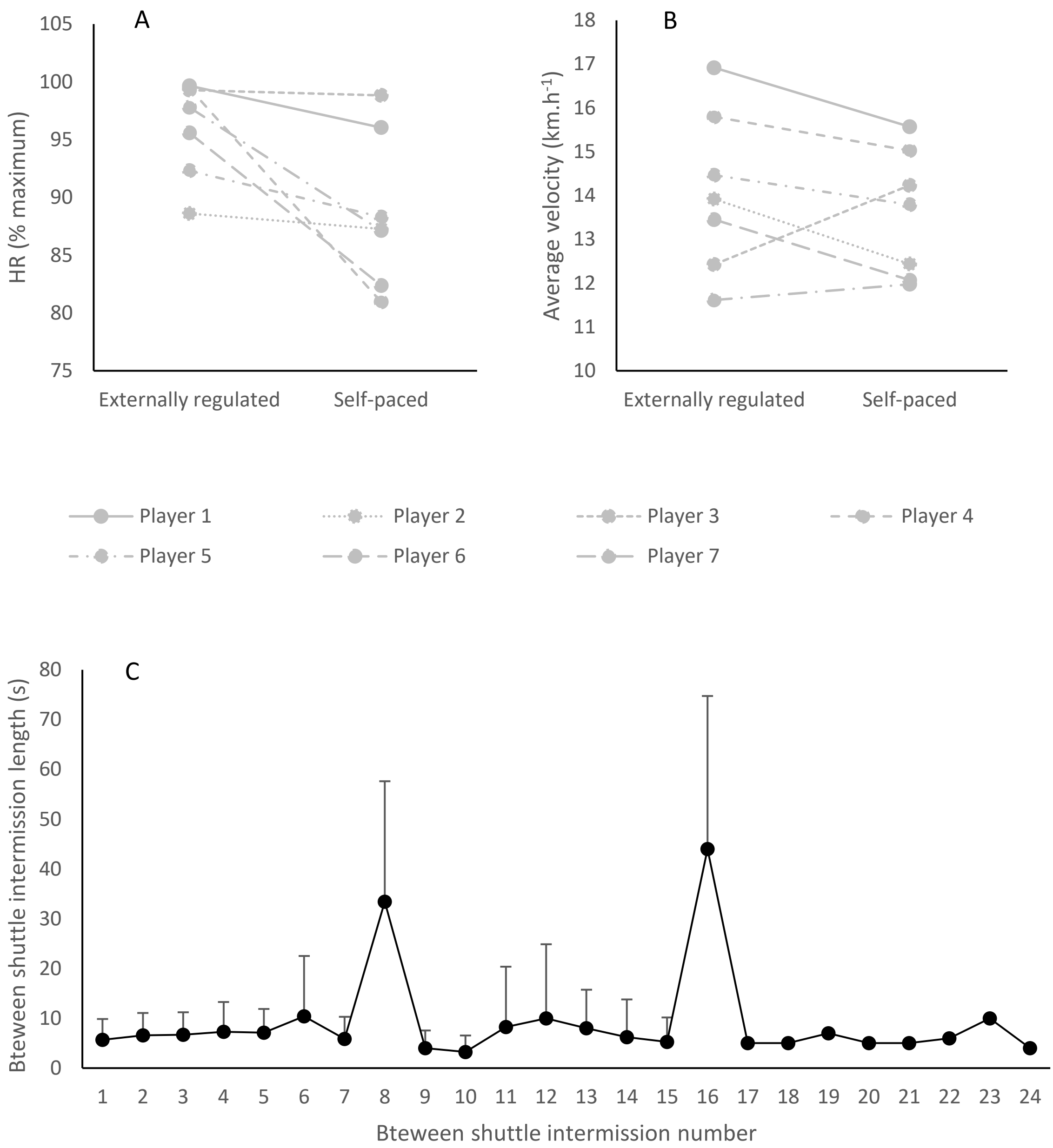


Figure 15: HR (% maximum) (A), average velocity (km·h^{-1}) (B) for each player and average between shuttle recovery periods for all players (C) in the self-paced version of the YYIRT1 at RPE values in the somewhat hard intensity band (16-18).

7.3.6 Intensity band comparison: RPE 19-20 [maximal]

Individual data for HR (% maximum) and average running velocity for externally regulated and self-paced versions of the YYIRT1 along with average between shuttle recovery duration in the self-paced versions of the YYIRT1 are presented in Figure 16 A-C. Small differences in peak running speed (1.8%; ES 0.23 ± 0.2; P = 0.92) were observed in the externally regulated compared to self-paced version; there were trivial differences in average running speed between versions of the YYIRT1 (0.4%; ES 0.04 ± 0.2; P = 0.74). There were trivial differences in PlayerLoad^{TM} (3.2%; ES 0.18 ± 0.15; P = 0.48) whilst the average percentage of heart rate maximum was *most likely* higher (6.8%; ES 1.5 ± 0.4; P = 0.19) in the externally regulated compared to self-paced versions of the YYITR1. Differences in total recovery duration were trivial*;* the average between shuttle recovery duration was 10 s with a minimum of 0.0 and maximum of 108 s. Data relating to running performance and physiological responses at each intensity band are detailed in Table 8.

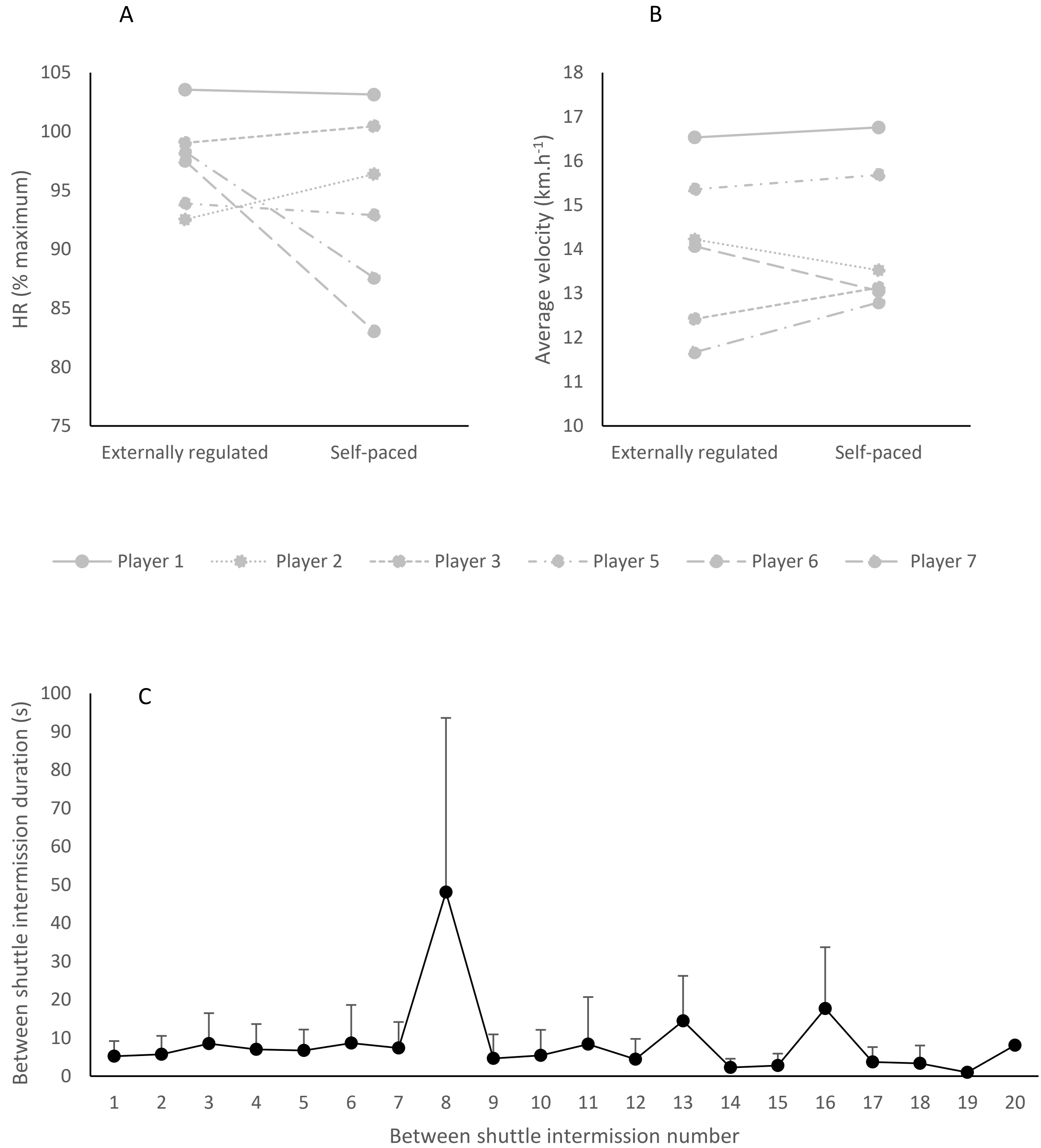


Figure 16: HR (% maximum) (A), average velocity (km·h^{-1}) (B) for each player and average between shuttle recovery periods for all players (C) in the self-paced version of the YYIRT1 at RPE values in the somewhat hard intensity band (19-20).

7.3.7 Comparison of self-paced version of the YYIRT1

There were small differences in total recovery time (13%: ES 0.5 ± 0.76; P = 0.07) between the second [470.5 ± 131.5 s] self-paced trial and the first [530.8 ± 113.2 s] whilst the average between shuttle recovery length was *likely* (15.8%; ES 0.78 ± 0.9; P = 0.06) less in the second compared to first trials [9.8 ± 1.5 cf. 8.4 ± 2.1 s respectively]. There were moderate (7.7%; ES 0.69 ± 1.06; P = 0.22) differences in the maximal running velocity [21.6 ± 1.9 cf. 20.1 ± 2.7 $km \cdot h^{-1}$] and average running velocity (9.4%; ES 0.96 ± 1.36; P = 0.17) achieved in each trial [13.8 ± 1.0 cf. 12.7 ± 2.4 $km \cdot h^{-1}$]. There were trivial differences in the heart rate (% maximum) [90.4 ± 6.4 cf. 89.6 ± 7.5%] and maximal heart rate (1.0%; ES 0.13 ± 0.47; P = 0.4) between trials [191.5 ± 10.7 cf. 188.5 ± 8.4 $b \cdot min^{-1}$]. PlayerLoad™ per minute was *likely* (13.8%; ES 1.14 ± 1.4; P = 0.05) lower in the second [18.2 ± 3.9 $AU \cdot min^{-1}$] compared to the first self-paced trial [20.8 ± 1.9 $AU \cdot min^{-1}$]. There were trivial differences in total distance (2.9%; ES 0.09 ± 0.2; P = 0.5) between trial one [2210.0 ± 523.9 m] and trial two [2290 ± 626 m]. The distribution of between shuttle recovery durations for one player are detailed in Figure 17.

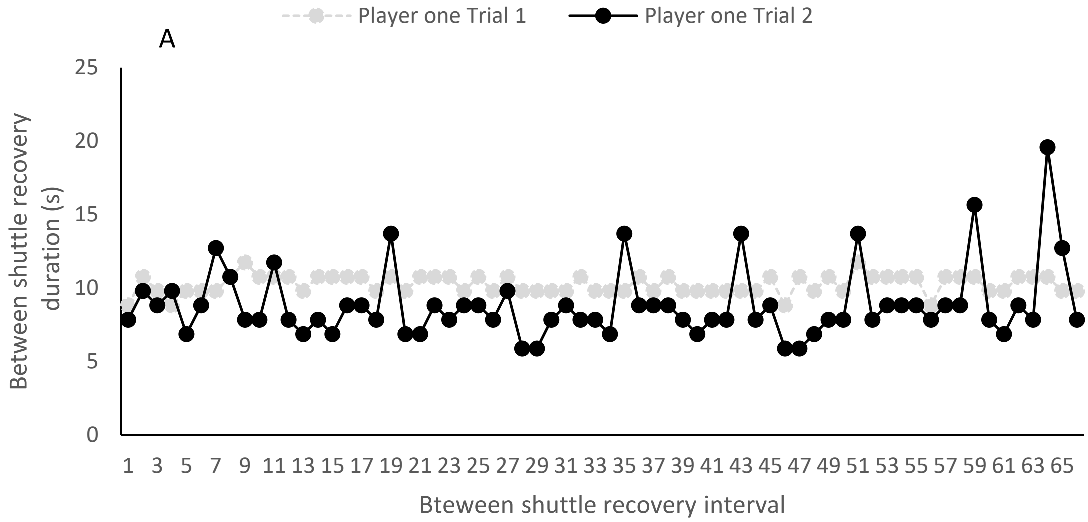


Figure 17: A, B, C and D: Recovery distribution for four players during repeated versions of the self-paced YYIRT1.

Table 8. Average ± SD for peak and average running speeds, percentage of heart rate maximum, PlayerLoad^{TM} and recovery duration in the externally regulated and self-paced assessments of high speed running ability. Magnitudes of difference between trials are indicated by: ***likely, $^{\$}$most likely † very likely. Values without symbols did not meet the 75% probability threshold.

	Peak running speed ($km \cdot h^{-1}$)		Average running speed ($km \cdot h^{-1}$)		PlayerLoad$^{TM} \cdot min^{-1}$ ($AU \cdot min^{-1}$)		Average HR (% max)		Recovery duration total (s)		Mean between shuttle recovery duration (s)
RPE band	ER	SP	ER	SP	ER	SP	ER	SP	ER	SP	EP
6-11 (light)	17.5 ± 1.5	16.3 ± 3.3 ***	13.2 ± 1.4	12.5 ± 2.8 ***	19.2 ± 2.6	19.8 ± 3.6	63.2 ± 40.4	66.7 ± 25.6 †	138.6 ± 103.3	138.7 ± 136.4 **	7.3 ± 3.4
12-13 (somewhat hard)	18.3 ± 1.6	15.8 ± 2.5 †	13.6 ± 1.6	11.8 ± 2.3 †	21.4 ± 3.3	20.7 ± 3.3 ***	69.2 ± 41.1	74.0 ± 9.9 $^{\$}$	90 ± 40.1	63.7 ± 58.1 ***	7.9 ± 7.3
14-15 (hard)	18.2 ± 0.8	15.4 ± 1.4 $^{\$}$	12.9 ± 1.05	10.9 ± 1.6 $^{\$}$	21.5 ± 3.1	20.5 ± 2.9 **	92.8 ± 5.7	78.4 ± 7.2 $^{\$}$	160 ± 56.6	122.8 ± 42.9 **	17.5 ± 23.6
16-18 (heavy)	18.9 ± 17.9	17.9 ± 1.9 $^{\$}$	13.8 ± 1.6	13.2 ± 1.5 ***	23.1 ± 3.3	22.5 ± 2.7	92.8 ± 5.1	84.5 ± 8.3 $^{\$}$	135.7 ± 62.1	140.7 ± 71.6	10.7 ± 3.7
19-20 (maximal)	19.4 ± 1.4	19.1 ± 2.3 **	14.0 ± 1.6	13.9 ± 1.6 $^{\mu}$	25.1 ± 4.4	25.8 ± 3.8	94.9 ± 4.3	88.9 ± 8.8 $^{\$}$	135 ± 52.4	128.2 ± 65.2	9.8 ± 4.3

7.4 DISCUSSION

This is the first study to compare movement characteristics and physiological responses during an externally regulated YYIRT1 versus a self-paced version. Although there were only trivial differences in total distance covered and maximal heart rate, variability in movement characteristics, between shuttle recovery duration and physiological responses were reported between trials. In each intensity band, peak and average running speeds were higher in the externally regulated version of the YYIRT1, however the magnitude of these differences was less pronounced in the *maximal* intensity band (RPE 19-20). Similar to data reported in Chapters 5 and 6 for repeated sprinting, total recovery during the self-paced trial was lower than when externally regulated. The lower allocation of recovery did not result in higher heart rate, as was the case in Chapters 5 and 6, in the self-paced version of the YYIRT. This is most likely as a result of the stochastic nature in which recovery was selected.

During the externally regulated trial, total recovery time was higher than in the self-paced trial with trivial differences in average between shuttle recovery periods. Figure 11 (group) and 17 (individual) demonstrates the distribution and stochastic nature of between shuttle recovery periods, evidenced by players completing a number of shuttles with limited or no recovery before an extended period of rest. The stochastic approach to recovery allocation is different to that observed in Chapters 5 and 6 when repeated sprints were interspersed by self-selected recovery periods. Despite this, data here and that in Chapters 5 and 6 collectively point to academy footballers increasing between interval recovery duration when running performance has begun to deteriorate. This is different to the approach seen in adults during high intensity running (McEwan et al., 2018) and repeated sprinting (Phillips et al., 2014) and during which recovery periods were elongated in an anticipatory manner to preserve performance. It suggested that academy footballers exhibit a reactive approach to recovery allocation when allowed to self-select this variable. In Chapters 5 and 6 reductions in sprint performance of a *likely* and *most likely* magnitude were seen before increases in recovery duration of a similar magnitude. The stochastic approach to recovery allocation observed here means that players are not allowing themselves time between successive shuttles to interpret their performance and decide whether more (or less) recovery is required. This is in contrast to adults who have been shown to exhibit 'anticipatory' strategies for recovery allocation, adopting longer recovery periods from the outset to preserve performance (McEwan et al., 2018; Phillips et al., 2014). Reducing self-selected between sprint recoveries by 10 percent did not result in impaired performance in adults (Phillips et al., 2014). In Chapter 6 advanced biological maturity was suggested as a factor in players developing a more anticipatory approach to recovery allocation, however, the age of players in this study would suggest a fully mature state. Whilst advancing maturity may assist in the development of anticipatory strategies for the allocation of recovery during intermittent exercise, experience of training using the same method may also be important. Participants in the work of McEwan et al. (2018) engaged regularly in high intensity interval training, some of which was self-directed rather than prescribed (McEwan et al., 2018). Common practice for academy footballers is to have conditioning training externally regulated by a coach or sport scientist using predefined work to rest periods. Exposing academy players to training and testing protocols that require them to self-pace the exercise intensity and recovery duration during intermittent high intensity training may be a useful addition to their development, enabling them to develop skills in the anticipatory allocation of recovery at an early age. This may be especially important if they have to play with chronologically older players and/or when transitioning into adult competition.

Total recovery time and average between shuttle recovery times showed greater variation between successive self-paced versions of the YYIRT1 than peak and average running speeds or maximal heart rate. These data suggest that more than two trials are required for academy footballers to adopt an approach to recovery allocation that can be seen as stable. Whether the allocation of recovery in such a self-paced assessment would be stable following multiple trials or whether an optional strategy for the allocation of recovery exists unclear. Previous research has shown that adults require nine attempts to develop an optimal pacing strategy for completion of a time trial performed on a cycle ergometer (Foster et al., 2001) the protocol for which was continuous with no requirement for recovery periods to be allocated.. In Chapter 4 the observed movement characteristics during externally regulated high speed runs and repeated sprints where similar, despite large differences in the speeds used in their prescription. These findings suggest that future research should consider the variability and distribution of recovery time along with the fidelity of running speed during high speed running to identify whether such a protocol can be used longitudinally in the monitoring of academy footballers.

Although the validity of whole body loading assessed using global positioning technology has also been questioned (Nedergaard et al., 2017), PlayerLoad^{TM} has been shown to exhibit moderate to high reliability during football actions that include jogging, striding and sprinting (Barreira et al., 2017). In Chapter 4 PlayerLoad^{TM} was higher when high speed running was combined with repeated sprinting than when performed in isolation, indicative of the high musculoskeletal load associated with higher peak speeds in the current chapter. There were differences between trials in PlayerLoad^{TM} values with higher values reported in the externally regulated trial with the exception of exercise in the *light* (6-11 RPE) and *maximal* (19-20 RPE) intensity bands. The author's experience suggests that during the YYIR1 players move off the start line prior to the audio signal which results in altered acceleration mechanics and/or modification of turning mechanics depending on whether they are ahead or behind the beep at the half way point in each 40 m shuttle. In a modified version of the YYIR1 in which players were required to adopt a prone position at the start of each new 40 m shuttle PlayerLoad^{TM} values were higher than in a traditional version of the assessment, highlighting the effect that how each shuttle is started can affect musculoskeletal load (Dobbin, Moss, Highton, & Twist, 2018). The self-selected recovery trial, however, allowed players to initiate the accelerative phase of each shuttle under their own volition and without the external audio cue. This may have contributed to the lower PlayerLoad^{TM} values observed in this version of the assessment. More work is required to understand the effect that external cues have on start and turn mechanics when performing shuttle running compared to when under self-paced conditions. The magnitude of difference in PlayerLoad^{TM} was highest for the *somewhat hard* intensity band that also corresponded to the largest (*very likely*) differences in both average and peak running speed. It is possible that because the self-paced version of the protocol was based on RPE values obtained during the externally regulated version, differences in running speeds were not of a sufficient magnitude to affect PlayerLoad^{TM}. Coaches and practitioners should not be concerned with any increase in musculoskeletal load associated with self-paced versions of the YYIRT1 however should consider whether during exercise that requires players to accelerate from a stationary position the effect that external audio cues may have on these mechanics and associated musculoskeletal load.

Although peak heart rates at the end of each trial were similar, there was variability in the way they were reached under self-paced and externally regulated conditions (Figure 18). In the first two intensity bands, *light* and *somewhat hard*, the average heart rate (% maximum) was higher in the self-paced version. These data are likely explained by players allocating less between shuttle recovery (9.0 and 7.0 s, respectively) than in the externally regulated trial (10 s). This finding is consistent with data reported in Chapters 5 and 6 and also during 5 x 1000m running intervals (Edwards et al., 2011) in which higher heart rate was reported when self-selected recoveries were used compared to when externally regulated. Within *hard, heavy* and *maximal* intensity bands however, heart rate was higher in the externally regulated compared to self-paced trial. This is likely because of faster average and maximum running speeds along with the stochastic approach to recovery described earlier resulting in multiple shuttles with limited or no recovery. Figure 18 illustrates for one player how the less frequent but extended periods of recovery resulted in a lower heart rate response in the self-paced trial. Indeed, this was a strategy adopted by five of the seven players, with long but less frequent recovery periods interspersing shuttle runs. These data show that whilst both versions of the protocol were intermittent in nature, the self-paced trial was not incremental evidenced by non-linear increases in heart rate and running speeds. This finding supports data presented in Chapter 4 which showed the movement characteristics of high intensity running and repeated sprinting do not reflect the speeds they were prescribed at, challenging the fidelity of self-paced exercise when the intention is to approximate an externally controlled speed. Collectively these data suggest that academy footballers may not be able to differentiate between different intensities of high speed running when externally regulated (i.e. Chapter 4) or anchored to RPE.

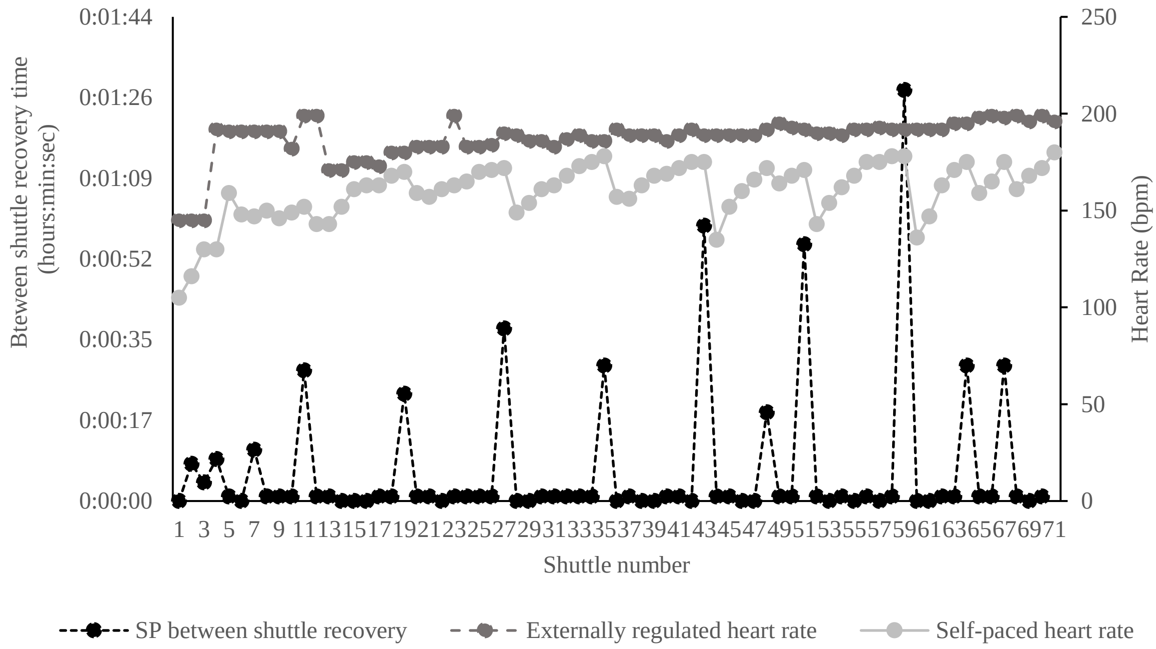


Figure 18: Recovery duration and distribution along with corresponding heart rates for the self-paced (light grey solid line) and externally regulated (dark grey dotted line) versions of the YYITR1.

Academy footballers are able to achieve a similar performance in terms of total distance during assessments of high speed running ability under externally regulated and self-paced conditions. Indeed, in adult footballers, the relationship between perceived effort and running performance during training and match play is stronger for total distance than for other, commonly cited indices, including running speed (Bartlett, O'Connor, Pitchford, Torres-Ronda, & Robertson, 2017; McLaren et al., 2018). Furthermore, trivial differences in maximal heart rate at volitional exhaustion suggest that both assessments elicited similar peak cardiovascular responses. These findings suggest that self-paced versions of the YYIRT1 are suitable for the physical assessment of academy footballers where the aim is to establish high speed running capacity and maximal heart rate values for use in the quantification of subsequent training load (Stagno et al., 2007). However, the methodological approach used should be considered when interpreting these data. The externally regulated trial was performed first to provide RPE values that the self-paced version could be anchored to; when the point of volitional exhaustion in the externally regulated version was reached in the self-paced trial no further feedback on anchor RPE values was provided. This had two effects; 1) provided a target in the self-paced version to reach the point at which no further RPE feedback and match total distance covered in the externally regulated trial, and 2) compromise motivation to continue to exercise in the self-paced trial beyond the point of exhaustion in the externally regulated version, even if the players felt able to do so.

7.5 CONCLUSION

Total distance and maximal heart rate were similar in both the self-paced and externally regulated versions of the YYIRT1 suggesting that the former method of administering the protocol results in values that can be used to assess maximal high intensity running ability and to establish peak heart rate values for academy footballers. Despite this, how maximal heart rate values are attained within each trial appears to be different. During the self-paced version of the YYIRT1 academy football players allocate less total recovery and distribute this in a stochastic and non-uniform manner when compared to the externally regulated version. As a result, peak and average running speeds in each of the intensity bands and heart rate as a percentage of maximum in the *hard*, *heavy* and *maximal* intensity bands were lower in the self-paced compared to externally regulated version. Differences between the trials in PlayerLoad^{TM} were of a smaller magnitude and suggest that the musculoskeletal load associate with running, turning and accelerative actions is not different between externally regulated and self-paced versions of the assessment.

7.6 PRACTICAL APPLICATIONS

The self-paced version of the YYIRT1 offers coaches and sport scientists a different method by which to assess high intensity running ability in academy football players through the modification of existing and validated protocols. Such an approach allows both the identification of maximal high intensity intermittent running ability and corresponding heart rate whilst exploring individual preferences relating to preceding running speeds and recovery distribution. Understanding more about how players choose to apportion recovery between bouts of high intensity running may allow practitioners to develop more individualised training programmes whilst developing a better understanding of movement characteristics observed during match play where running speed and recovery periods are not pre-defined or uniform.

Assessing high intensity running in this manner may also allow practitioners to identify a range of objective exercise intensities that correspond to the same RPE during controlled running drills. By tracking such responses longitudinally, practitioners may be able to identify when players are performing a greater amount of external load at the same RPE or, conversely when less external load is performed. In both scenarios such information may help practitioners more effectively schedule training and or manage load amongst academy players.

CHAPTER EIGHT

8.1 GENERAL DISCUSSION

The aim of this thesis was to investigate the movement characteristics, physiological and perceptual responses of adolescent footballers during football specific exercise in which they were required to self-pace high speed running whilst self-pacing the recovery periods that intersperse them. The data presented in Chapters 4-7 suggest that when adolescent football players self-pace high speed intermittent running and repeated sprinting, along with the recovery intermissions that intersperse them, that physiological load evidenced by heart rate and blood lactate is higher than when running speed and the length and distribution of intervening recovery periods are externally controlled. Conversely, the associated running speeds are slower whilst perceptual responses are similar. Collectively these data suggest that where the intention of training is to increase physiological load, for example, during pre-season training, high speed running and repeated sprinting that is self-paced and interspersed by self-selected recovery periods may be appropriate. Where there is a requirement to maintain running speeds, however, their use may be inappropriate. Furthermore, whilst maturation may improve the ability of adolescent players to pace intermittent high speed running and apportion recovery time effectively to achieve a stated aim, other factors contribute to the development of these skills through to a fully mature, adult state.

The data contained within this thesis shows that when academy footballers are exposed to discrete high speed running tasks interspersed with self-selected recovery periods, running speed and percentage decrement are compromised. Furthermore, during high speed running and repeated sprinting in training and assessment protocols, the ability of academy players to replicate prescribed speeds or those associated with specified ratings of perceived exertion is impaired. These data raise questions regarding how training is prescribed for academy footballers where the aim is to improve performance during competitive matches that are characterised by autonomy over movement demands and the intervening recovery periods. Although there is somewhat of a leap between data collected in controlled running trials and match play, the data presented here improves our understanding of how we interpret the performance of players in both training and competitive scenarios and how the former can be manipulated to be more representative of the latter. Indeed, in applied environments it is common for academy players to be judged on the amount of high speed running they perform rather than their ability to effectively apportion effort in line with the demands of the environment. This thesis shows that when compared to externally controlled work to rest ratios the performance of academy footballers in high speed running tasks was impaired under self-selected conditions, despite competing at an elite level in their domestic competition. Whilst physical capacity has been shown to differentiate between players of differing standards in adult (Stein, Gabbett, Townshend, & Dawson, 2015) and adolescent players (Waldron & Murphy, 2013) within elite demographics, these qualities are more homogenous in nature (Helgerud et al., 2011). As such, assessing and improving the ability of academy footballers to know how best to use the physical attributes they possess may be something coaches and practitioners prioritise in their training (Gibson & McCunn, 2018).

High speed running and repeated sprinting are activities performed by academy footballers during training and match play as well as forming component parts of the physical assessment protocols administered within this population. During match play and training, players are able to select running speeds and intervening recovery periods in response to the actions of opponents, tactical constraints and their own perception of fatigue in light of how long is left in the match or training session. In adult players, temporary reductions in high speed running during match play that occur after the most intense periods have been associated with fatigue

(Di Mascio & Bradley, 2013) rather than a conscious choice by the individual to reduce their work rate. Although players self-select the duration and distribution of between effort recovery periods during match play, this environment, given its non-uniform structure, does not lend itself to the study of recovery interval length and distribution effects subsequent running performance. This is largely the result of the myriad choices which may inform whether to 'stop' or 'go' including but not limited to playing position and quality of opponent, score line or coach encouragement. There is value however in understanding the ability of academy players to effectively pace running speed and apportion recovery duration so that they are able to maintain physical, if not technical performance across multiple high intensity bouts of exercise. To address this issue the performance of academy footballers in discreet running tasks was assessed under conditions which required them to interpret both temporal and spatial cues to pace running speed and recovery duration during high speed running and repeated sprinting.

To assess the ability of academy players in allocating recovery to maintain performance during high speed running intervals, it was important to investigate their ability to interpret the demands of such intervals. In applied practice, high speed interval running is typically performed in the field with players covering a pre-determined distance in a set period of time that reflects a speed associated with a particular physiological threshold, for example maximal aerobic speed (Buchheit & Rabbani, 2014; Dupont et al., 2004). A key finding of Chapter 4, however, was that the actual movement characteristics associated with high speed running and repeated sprinting performed in the field exhibited a greater degree of similarity than the speeds used in their prescription. As such the fidelity of this approach to training prescription was relatively poor and, furthermore, players were unable to differentiate between the demands of each drill. It was also apparent that despite differences in the movement characteristics and physiological responses (objective) associated with high speed running and repeated sprinting, this was not reflected in ratings of perceived exertion. In Chapter 7 academy footballers consistently ran at slower peak and average running speeds during a self-paced assessment when exercise was anchored to specified RPE collected during an externally regulated version of the same protocol. As such the ability of RPE to reflect measures of external and internal load during high speed interval training and also the ability of academy football players to interpret the temporal cues necessary for high speed running prescription in a field environment should be questioned. Coaches and practitioners should consider assessing the fidelity of the training practices they employ to assess how closely players perform what is being prescribed for them, and, furthermore, whether this matters in terms of monitoring longitudinal changes in fitness. Where players are being asked to cover a specific distance in a pre-determined time, coaches should consider whether players have the spatial skills to achieve this whilst maintaining the intended speed and/or intensity.

Chapters 5 and 6 used repeated sprints separated by self-paced and externally regulated intermissions to investigate the ability of players to interpret temporal cues during high speed running to effectively apportion recovery. By using shorter distances and exercise of a maximal nature with specific instructions regarding the aim of the assessment, players were able to focus on the effective allocation of recovery time rather than running speed as in Chapter 4. Data from Chapters 5 and 6 suggest that academy footballers are less able to effectively apportion recovery during repeated sprinting and that, consequently, their ability to maintain performance across each repetition is compromised. Performance decrements appear to be the result of self-selected recovery periods shorter in duration than would be allocated during protocols with similar interval lengths and intensities but governed by externally regulated work to rest ratios (Spencer et al., 2005). These findings are in contrast to those reported in adults who have been shown to effectively maintain performance when given autonomy over the duration and distribution of recovery intermissions during repeated sprinting performed on cycle and treadmill ergometry (Glaister et al., 2010; McEwan et al., 2018; Phillips et al., 2014). Such data suggest that at some point during the transition from youth to adulthood, individuals acquire the ability to interpret temporal cues and the ability to allocate appropriate recovery periods to maintain performance through a strategy that is 'anticipatory' in nature (Phillips et al., 2014). One such process by which this may occur are advances in cognitive development (Chinnasamy et al., 2013; Piaget, 1954). Although cognitive development was not assessed in this thesis, Chapter 6 shows that the ability to maintain performance across repeated sprints when self-selecting recovery improves with advancing biological maturity. This has implications in the prescription of training which comprises a degree of pacing, either in running speed or the allocation of recovery, and raises questions regarding whether these abilities might be improved in younger athletes if they are exposed to their use from an earlier age. It is the author's experience that most drills and training practises employed with academy footballers are externally regulated with clear indications from coaches regarding when to start, stop and recover from high intensity interval training.

To try and improve the ability of academy footballers to anticipate the demands of high intensity exercise and adopt approaches to recovery allocation that preserve running performance, a number of training modalities can be adopted which are detailed below:

High speed running with self-selected recoveries

The effective programming of such training requires coaches to make the aim of high speed running intervals separated by self-selected recovery explicit. For example, asking players to perform repeated sprinting whilst allocating *sufficient* recovery so to replicate their initial sprint performance across subsequent repetitions; or, performing high speed running allocating the *minimal* amount of recovery to ensure they meet the target speed in all repetitions. The approach to each of these challenges should be quite different, with longer recovery periods in the former and shorter, more uniform in the latter. Feedback can be used to help players understand how they can modulate their strategy for recovery allocation to achieve the demands using internal and external load data.

Self-paced time trial challenges

Within the literature there are protocols for the prescription of high speed running and repeated sprinting to enhance different facets of football specific fitness (Haugen et al., 2015; Ingebrigtsen et al., 2013; Tonnessen et al., 2011). The total time for these protocols can be used to challenge the ability of players to allocate recovery and pace their effort so to achieve the desired outcome under self-paced conditions. For example, 15 x 15 s runs at maximal aerobic speed interspersed by 15 s recovery equating a total time of 7.5 min has been shown to be effective at improving high intensity running ability (Dupont et al., 2004). An alternative approach is to ask players to perform the same number of intervals (15) in 7.5 min but without stipulating a work to rest ratio. Furthermore, only intervals in which they achieve the target speed are recognised. In this instance players must consider how much recovery to allocate whilst monitoring how it is affecting running speed; if they allow too little recovery and as a result run too slowly, the effort will not be recognised and will elongate the total time (and distance) they are required to work for. Such an approach may be more useful in periods where coaches and practitioners are less concerned with how much load players (for example pre-season) are exposed to as in the above scenario there is potential for more intervals than was originally intended to be performed.

Self-paced recovery during small sided games

Small-sided games are often prescribed with uniform between game recovery periods; however, an alternative approach is to allow the 'winning' or 'losing' team to allocate between game recovery duration. In applied practice, the winning team allocate less recovery than the losing team which requires both teams to adapt their strategy in the subsequent game so to achieve a competitive advantage.

In each scenario detailed above the physiological and external load experienced by players is likely to be less controlled than if uniform recovery periods are used and as such they may be used sparingly or at specific times in the season. The use of drills that require some self-pacing may be more appropriate where specific fitness aims are to be realised in older players or in players who, through early exposure, have developed the ability to self-regulate running speed and recovery to match the stated aim.

Chapters 4, 5 and 6 include data that suggest exercise incorporating some element of self-pacing may be beneficial in the physical conditioning of academy footballers via associated increases in physiological load. In Chapters 5 and 6 the physiological load associated with repeated sprinting separated by self-selected recovery periods was greater, when assessed using heart rate and blood lactate concentration (Chapter 5), than when interspersed by externally regulated intermissions. Given that training programmes for academy players are often part time in nature, the prescription of high speed running using self-selected recovery periods may be an attractive option for coaches and practitioners because of increased physiological load and shorter time to complete (because of shorter between interval recovery periods). The higher physiological load supports their use during periods when coaches and practitioners are programming for adaptation, as an example, during the pre-season period. Furthermore, removing the requirement of a coach to inform players of when to start and stop can facilitate training of this nature being prescribed for the players to perform away from the academy, freeing up contact time with coaches for more tactical and technical elements of training. There may also be instances where coaches wish to try and improve the speed at which players complete high speed running at. Whilst chronic approaches have been shown to achieve high intensity running speed (Faude et al., 2013; Ingebrigtsen et al., 2013), data from Chapter 4 highlighted that by performing repeated sprints before high intensity running, the speed at which the latter was performed increased, compared to when scheduled in series.

The data reported in this thesis suggest that performing high speed running and repeated sprinting using externally regulated or self-paced recovery periods had no detrimental effect on neuromuscular function assessed via a countermovement jump. Such data should allow coaches and practitioners to consider their use in close proximity to match play, a time when academy players likely want to feel able to give their best performance. This is important when training academy football players as experience would suggest that due to the inclusion in multiple squads across a week, the training load for players could be markedly reduced, especially if they do not play in the squads they have been selected for. Indeed, a similar response has been reported for first team players not included regularly in match day squads (Anderson et al., 2016). An example week for a sixteen year old, full time professional academy player may involve two matches but only two training sessions because of how recovery days and low load training sessions preceding matches are scheduled. Data from academy footballers has suggested that over a 6 week period, time spent above maximal aerobic speed has a strong relationship with positive changes in this maximal aerobic speed over the same period, achieved via an average weekly total of 8 minutes (Fitzpatrick et al., 2018). This finding is despite players not performing any specific running drills aimed specifically at achieving maximal aerobic speed. In Chapter 4 it was shown that 12 x 15 s of high speed running resulted in approximately 40 s of time at the final speed achieved in the YYIR1, representative of 20% of the target exercise time. As such performing 3 sets of this type of drill on two days per week supplementary to squad training would seem appropriate for the development of high speed running ability in players with a reduced training load. The knowledge that high speed running and repeated sprinting can elicit physiological loads commensurate with improvements in aerobic fitness without compromising neuromuscular performance in the following days would allow coaches and practitioners to more effectively programme and periodise training for these groups. Despite different movement characteristics, total recovery and physiological load, Chapters 5 and 6 did not detect any differences in the perceived exertion between repeated sprinting separated by externally regulated and self-paced recovery periods. This is important for practitioners and clubs who rely on subjective markers of intensity for longitudinal training and training prescription.

Although the use of RPE to establish the subjective intensity of training has been reported for academy footballers (Akubat et al., 2012) few studies have investigated how closely players are able to replicate the demands associated with specific RPE values collected during externally regulated exercise. Data from Chapter 7 suggests that when performing self-paced high speed running at RPE-derived intensities collected during externally regulated exercise, academy footballers run at slower average speeds whilst apportioning less overall recovery. In terms of recovery duration and running speed, these data reaffirm those reported in Chapters 5 and 6; however, not for physiological load. In Chapters 5 and 6 less recovery allocation was associated with higher RPE values, whereas in Chapter 7 exercise performed above an RPE of 14 also resulted in more recovery during the self-paced trial yet physiological load was lower. This was likely the result of a stochastic approach to recovery allocation whereby players performed multiple shuttles with little or no rest before taking an extended break during which heart rate was reduced. Although the same stochastic approach to recovery was not observed in Chapters 5 and 6, collectively, the data points toward academy players adopting a 'reactive' rather than 'anticipatory' pacing strategy. This is evidenced by players extending their between effort recovery periods after decrements in performance of a *likely* and *very likely* magnitude rather than doing so in a more anticipatory manner to avoid decrements in performance before they manifest. It would appear that whilst biological maturation improves a player's ability to adopt a more anticipatory approach, greater exposure to exercise that is self-paced may be a useful addition to the development of academy players, especially given the non-uniform nature of high intensity efforts and recovery periods during match play.

8.2 STRENGTHS, LIMITATIONS AND FUTURE RESEARCH

8.2.1 Strengths

High speed running and repeated sprinting are employed by coaches and sport scientists to condition academy footballers. Chapter 4 in this thesis is the first study to question the fidelity of this approach when training of this nature is conducted in the field and highlights a disparity between what is prescribed and what is actually performed by the players. These data should prompt coaches and practitioners to query how closely what players do in the field matches what has been prescribed for them. Furthermore, it highlights the importance of research which has shown running of this nature to be effective in the training of academy football players (Faude et al., 2013; Ingebrigtsen et al., 2013; Tonnessen et al., 2011) to detail the internal and external loads associated with each session so that a greater understanding of the dose-response relationship can be sought. Chapters 5 and 6 detail a novel way of prescribing repeated sprint training that in academy footballers achieves a higher physiological load than when prescribed with uniform recovery periods. This novel approach is easy to administer and can be performed away from the training ground without the need for additional equipment or coach input. Finally, the data within this thesis when viewed collectively should prompt coaches and practitioners to interpret fitness testing data with a degree of caution; the data shows that when self-selected recoveries are employed, some players are able to augment their performance during repeated sprinting whilst the advantage of being biologically less mature is reversed evidenced by greater percentage decrement compared to more mature players. It is also apparent, as demonstrated in Chapter 7 that when measures of high intensity running ability are self-paced, the way players achieve maximal values is very different to performance governed by external cues. Given the importance many clubs place on measures of physical quality in the selection and retention of players the data contained herein should prompt those responsible for choosing and implementing these protocols to carefully consider which protocols they use and their appropriateness for different ages within the academy structure.

8.2.2 Limitations

The studies presented in this thesis are all applied in nature and conducted with academy footballers registered at a professional football club, as such, the measures and assessments were to some extent limited by the training schedule, player availability and a desire to not disrupt normal training practises.

The measures used to quantify physical performance in this thesis were indirect and as such there is no exploration of the internal mechanisms or underlying physiology. Chapters 5 and 6 would have benefited from the assessment of expired gases to explore whether the increase in heart rate during self-selected recovery trials was reflective of a higher percentage of maximal oxygen uptake. Furthermore, the use of the maturity offset equation in Chapter 6 has received critique in the literature with techniques such as Tanner staging and wrist x-rays being preferred for the determination of biological maturity. A more detailed exploration of neuromuscular function after the high intensity exercise in Chapter 4, such as those used by Goodall et al. (2015), would have allowed a more comprehensive analysis of the origins of fatigue (i.e. central vs. peripheral) and how each running drill affected this physical quality.

Although the YYIR1 is not used as a proxy for maximal aerobic capacity, the addition of cardiopulmonary data in Chapter 7 would have allowed a more detailed investigation of the route by which players achieved volitional exhaustion in both the externally regulated and self-paced versions and the effect on this variable that the stochastic nature of recovery allocation had. Additionally, this study would have benefited from a greater number of players performing the self-paced version of the YYIR1 on more than one occasion. Despite more players being recruited to the study, changes to the training schedule, unplanned fixtures and a mid-season break meant that a smaller number of individuals were able to complete all data collection sessions within the desired period.

Given the selection of players in this thesis from the same professional academy and, for some chapters from specific age groups and levels of maturation, some chapters when accounting for sample size calculation are under powered, specifically Chapters 5 and 7. Readers should consider this when interpreting the data.

8.2.3 Future research

Whilst biological maturation may influence the ability to effectively apportion recovery during high speed running activities (Chapter 6), the underlying factors that control this skill remain unclear. Further investigation is required to understand the cognitive, developmental and even cultural factors that may contribute to the ability to effectively pace intermittent high speed activity (Chinnasamy et al., 2013; Micklewright et al., 2012). Furthermore, although discrete bouts of high intensity activity interspersed with self-selected recovery resulted in higher physiological load than when recovery was externally controlled, whether this approach would be effective if prescribed chronically remains unknown.

The chapters in this thesis have shown that academy football players are, in discreet high speed running tasks, unable to apportion recovery duration to maintain sprinting performance or differentiate between the movement demands associated with running tasks of differing intensities. Further investigation is warranted to explore match activities in more detail to explore whether high intensity activities are conducted at the most appropriate times and with sufficient recovery to warrant an effort commensurate with the requirement of the environment.

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Appendix 1

Maturity offset equation cited in Mirwald et al., (2002)

29.769 + 0.0003007·Leg Length and Sitting Height interaction + 0.01177·Age and Leg Length interaction + 0.01639·Age and Sitting Height interaction + 0.445·Leg by Height ratio, where R = 0.96, R2 = 0.915, and SEE = 0.490.